

**BUSITEMA
UNIVERSITY**
Pursuing Excellence

FACULTY OF ENGINEERING AND TECHNOLOGY

DEPARTMENT OF WATER RESOURCES ENGINEERING

FINAL YEAR REPORT

**OPTIMIZING THE PHYSICAL AND MECHANICAL PROPERTIES OF BAMBOO
FIBER REINFORCED UNFIRED CLAY BRICKS.**

A CASE STUDY: BUSITEMA VILLAGE

By

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Final year proposal report is submitted to the department of water resources engineering in partial fulfilment of the requirement for the award of Bachelors of Science degree in water resources engineering at Busitema University.

DECLARATION

I OLWENYI HUMPHREY MUDANGO, registration number BU/UG/2022/1563, declare that the work in this project proposal is my original work and has not been presented to any higher institution of learning for any academic award.

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APPROVAL

I hereby certify that this project is original proposal report of OLWENYI HUMPHREY MUDANG0, BU/UG/2022/1563. It has been done under my supervision and is ready for submission to the department of water resources and mining engineering.

SUPERVISOR: MR TIGALANA DAN

SIGNATURE:

DATE:

DEDICATION

I dedicate this report to my Parent, Mr. Olwenyi mudango, my siblings, lecturers and my friends, may the almighty Lord reward you abundantly and give you good health.

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I would like to express my heartfelt gratitude to the Almighty for His constant guidance, protection, and blessings throughout this journey

To parents for their unwavering love and support, which have been the cornerstone of my achievements. Their sacrifices and encouragement that have fueled my ambition to pursue my dreams.

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CHAPTER I

1.0 Introduction

This chapter contains a problem statement, justification, objectives of the study, scope of the study.

Background

The fundamental human need for affordable and adequate housing faces critical barriers globally, nationally, and locally. The solution to the housing crisis must now align with urgent environmental goals of mitigating deforestation and reducing high embodied CO₂ emissions from the construction sector, particularly those generated by the production of fired clay bricks (*Fahri et al., 2023*)

Globally, approximately 1.8 billion people lack adequate housing (*McRae et al., 2022*) This overwhelming need drives a relentless demand for construction, escalating resource consumption. The construction and buildings sector contributes around 37% of total global energy and process-related CO₂ emissions, with a significant portion attributed to embodied carbon locked into materials during production (IEA, 2022). To meet the Paris Agreement goals, the sector must nearly fully decarbonize by 2050 (Build Change, 2024).

In Africa, rapid population growth and urbanization further exacerbate the housing deficit, while reliance on traditional practices intensifies environmental strain. Africa's population has grown from 810 million to 1.4 billion since 2000 (*Saifaddin Galal et al., 2023*) driving construction costs upward and pushing millions into informal, substandard dwellings (*Abimbola Olukemi et al., 2022*). The production of Fired Clay Bricks (FCBs) involves high-temperature kilning fueled by local wood, releasing significant CO₂ emissions and directly driving deforestation (*University of Warwick, 2017*).

Uganda faces a particularly severe crisis. The country has a critical housing deficit of over 2.4 million units, a number predicted to rise with population growth (*Watchdog Uganda, 2024*). The cost of conventional building techniques is so prohibitive that 96% of Ugandans cannot afford a formally constructed house (Watchdog Uganda, 2024). The widespread, artisanal production of FCBs relies overwhelmingly on wood fuel in inefficient kilns, making it a major driver of deforestation, biodiversity loss, and black carbon emissions (*Nakamya, 2008; Olweny et al., 2017*).

This study therefore investigated bamboo fiber reinforcement as a sustainable and locally available strategy to overcome the limitations of unfired clay bricks, delivering a high-performance, cost-effective, and low-carbon building material suited to Uganda's tropical context.

1.2 Problem statement

While unfired clay bricks offer a promising low-carbon solution by eliminating the firing process, their widespread adoption is hindered by inherent technical limitations in Uganda's tropical climate. Simple unfired bricks suffer from poor durability, low tensile strength, and vulnerability to moisture and cracking. Traditional stabilization methods rely on high proportions of cement, which is costly and reintroduces significant embodied CO₂, nullifying the environmental benefit.

There was therefore an urgent need to develop a high-performance, cost-effective, and low-carbon alternative. This project addressed this gap by investigating bamboo fiber reinforcement as a sustainable means to significantly improve the physical and mechanical properties of unfired clay bricks, ensuring their durability and structural resilience while maintaining their low-carbon, low-deforestation advantage.

1.3. Objectives

1.3.1. Main objective;

To optimize the physical and mechanical properties of bamboo fiber reinforced unfired clay bricks.

1.3.2. Specific Objectives:

- I. To characterize the clay brick materials, cement and the prepared bamboo fibers to assess their suitability and compatibility for brick production.
- II. To optimize the mix proportions of bamboo fiber, cement and clay for maximum structural integrity and environmental resilience in brick production.

III. To compare the fired clay bricks with the newly produced bamboo fiber reinforced unfired clay bricks.

1.4. Significance of the Study

This study addresses the global increase in carbon dioxide emissions and deforestation by exploring innovative construction methods. Its success delivers a low-carbon, resilient, and high-performance building component that addresses the affordability barrier to formal housing for vulnerable populations while simultaneously preserving natural ecosystems. The study contributes to SDG 13 (action to combat climate change and its impacts).

1.5. Justification of the study;

The study is justified by the need to develop a structurally sound, moisture-resistant, and affordable building material that eliminates the wood-fuel firing process, thereby directly mitigating widespread deforestation and construction-related CO₂ emissions in Uganda. By optimizing the mix of clay and bamboo, the study reduces reliance on energy-intensive materials such as reinforced concrete and steel, while enhancing strength and durability.

1.6. Scope of the study;

The study evaluated the mechanical and physical characteristics of bamboo fiber reinforced unfired clay bricks, used Response Surface Methodology (RSM) to optimize mix proportions, developed appropriate moulds for improved brick integrity, and tested the optimized bricks for environmental resilience. Testing was conducted at 7, 14, and 28-day curing intervals at the Busitema University Materials Laboratory.

2. LITERATURE REVIEW

2.1 Introduction to Unfired Clay Brick Construction

Unfired clay bricks, also known as sun-dried or adobe bricks, represent one of the oldest and most historically enduring construction materials, with evidence of their use dating back to at least 9,000 BCE in ancient settlements. This technology involves using a mixture of earth materials typically clay, silt, and sand, often combined with natural fibers shaped into units and air-dried rather than fired in a high-temperature kiln. Modern research has focused on enhancing their structural performance through stabilization and reinforcement while preserving their environmental advantages.

2.2 Soil Composition and Its Impact on Earth Brick Properties

The performance of clay brick structures is heavily influenced by soil composition. (*Maniatidis and Walker (2008)*) provided details of the particle distribution of earth bricks where clay and silt contents range from 10% to 80%. The acceptable range for compressed stabilized rammed earth (CSRE) is 5% to 40%, with a recommended range of 25% to 40%. Recent work by *Xu et al. (2024)* suggests that these proportions can be fine-tuned based on local soil characteristics to optimize performance.

2.2.1 Clay Content and Binding Properties

Clay plays a crucial role in binding particles together in clay bricks. *Sanchez-Haro et al. (2024)* found that the type of clay mineral present greatly affects the strength and durability of the bricks. Kaolinite-rich soils tend to produce stronger bricks compared to those rich in montmorillonite, as kaolinite resists expansion when wetted and undergoes less dramatic drying shrinkage.

2.2.2 Types of Clay Minerals

The three major groups of clay minerals are Kaolinite, Montmorillonite, and Illite. Kaolinite is a 1:1 type clay mineral composed of one silica layer and one alumina layer. Its strong inter-layer binding forces resist expansion when wetted, resulting in lower plasticity, reduced drying shrinkage, and suitability for making clay bricks (*Ochieng, 2016*). Illite minerals belong to the clay mica group of phyllosilicate minerals with a platy, flexible, and hydrophilic crystalline structure (*Unal and Mimaroglu, 2012*).

2.3 Bamboo Fiber as a Reinforcement Material

Bamboo has garnered significant attention as a sustainable building material due to its remarkable properties, including a high strength-to-weight ratio, renewability, and rapid growth cycle. Some bamboo species can grow up to 91 cm in a single day (*Binega & Memari, 2025*). Bamboo's tensile strength can range from 60 MPa to 193 MPa, while its compressive strength varies between 40 MPa and 60 MPa for loading applied parallel to the grain (*Binega & Memari, 2025*). These values are comparable to or surpass those of mild steel, making bamboo fibers a highly effective natural reinforcement.

2.4 Mechanical Properties of Earth Bricks

2.4.1 Compressive Strength

Khadka and Shakya (2016) show that the compressive strength of unsterilized soil varies widely between 0.25 and 0.6 MPa, and that properly compacted earth can achieve compressive strengths ranging from 1 to 5 MPa with optimal stabilization. Studies have demonstrated compressive strengths up to 10 MPa can be achieved, rivalling some conventional concrete mixes. The compressive strength of bamboo culm typically falls within the range of 40 to 80 MPa, attributed to its functionally graded structure with the highest fiber density in the hard outer culm layer (*Aicher & Simon, 2022*).

2.4.2 Tensile and Flexural Strength

Clay bricks excel in compression but their tensile and flexural strengths are relatively low. (*Danso (2016)* reports typical tensile strengths of 0.1 to 0.5 MPa for unsterilized earth, while showing that addition of natural fibers such as sisal or jute can increase tensile strength by up to 200%. The ultimate tensile strength of individual bamboo fibers can range between 100 and 350 MPa, due to the dense, longitudinal alignment of cellulose fibers within the lignin matrix (*Fahri et al., 2023*).

2.5 Role of Cement in Stabilization

Cement stabilization is a common method to enhance the strength and durability of unfired earth bricks. *Jayasinghe and Kamaladasa (2007)* reported that cement contents between 4% and 10% by weight can increase compressive strength of rammed earth by 300% to 500%. Cement contents of 6%, 8%, and 10% corresponded to strength increases of 41%, 80%, and 92% respectively compared to a reference mix. A life cycle assessment by *Tripura and Singh (2015)* concluded that medium cement content of 6% to 8% offers the best balance for most

applications, providing sufficient strength while maintaining significant environmental benefits over conventional materials.

2.6 Durability and Weathering Resistance

The durability of unfired earth bricks under tropical environmental conditions is critical.

Faraj et al. (2023) investigated the use of nanosilica and recycled plastics to improve water resistance and freeze-thaw durability, demonstrating that such additives can reduce water absorption by up to 70%. *(Tyoden et al. (2023))* found that 6% cement content can reduce water absorption by up to 50% in stabilized earth. *(Ben-Alon et al. (2013))* demonstrated that unfired clay brick buildings can reduce CO₂ emissions by up to 50% compared to conventional concrete structures over a 50-year lifespan.

2.7 Research Gaps

While extensive literature exists on natural fiber reinforcement of earth bricks using sisal, jute, and coir, limited research has specifically optimized bamboo fiber reinforcement parameters (content and length) for unfired clay bricks in tropical East African contexts using Response Surface Methodology. This study fills this gap by systematically applying RSM with CCD to identify optimal bamboo fiber-clay-cement combinations for maximum structural and durability performance.

3. METHODOLOGY;

Characterizing the clay brick materials, cement and the prepared bamboo fibers to assess their suitability and compatibility for brick production.

3.2.1 Characterization of Clay Brick Materials

Materials were characterized by their unique physical and mechanical properties following standard testing procedures. The characterization was based on strength, stiffness, durability, corrosion resistance, cost, availability, and workability.

3.2.2 Material Selection and Source

Clay soil was sourced from Busitema Sub-county, Busia District, Uganda. The sampling location was selected based on preliminary visual inspection indicating high clay content. Bamboo (*Bambusa vulgaris* species) was harvested from mature culms (aged 3–5 years) locally available. Ordinary Portland cement of grade 42.5 MPa was procured from a certified supplier for stabilization. (Tororo cement).

3.2.3 Tests Conducted on Soil Sample

The following standard tests were conducted on the soil sample: (i) Sieve analysis to determine particle size distribution; (ii) Atterberg limits test (liquid limit and plasticity index); (iii) Standard Proctor Compaction test for MDD and OMC; (iv) Moisture content test.

Sieve analysis test

A particle size distribution is a necessary classification test for soils, especially coarse soils, in that it presents the relative portion of different size particles. From this, it is possible to determine whether the soil consists of predominantly gravel, sand, silt or clay sizes and to a limited extent, which of these size ranges is likely to control the engineering properties of the soil.

Particles passing specific sieves and are retained on specific sieves are categorized as below;

Clay – particles passing 0.002mm sieve

Sand – particles passing 2.0mm and retained on 0.600mm sieve

Gravel– particles passing 200mm and retained on 63mm sieve

Boulders – particles passing 600mm and retained on 200mm sieve

References

BS 1377: Part 2: 1990

Apparatus used

Sieves (75mm, 63mm, 50mm, 37.5mm, 28mm, 20mm, 14mm, 10mm, 6.3mm, 5mm, 3.35mm, 2mm, 1.18mm, 600 μ m, 425 μ m, 300 μ m, 212 μ m, 150 μ m, 75 μ m)

Pan

Electric balance

Containers

Oven

Rubber mallet

Metal tray

Riffle boxes

Sieve brush

Procedures

1. Material in a given area was sampled and taken to the laboratory.
2. The material was air dried and the lumps in it were broken using a rubber mallet

The material was then mixed thoroughly and then riffled to obtain a representative sample.

3. The required sample was obtained and weighed to get the initial weight before washing. The initial weight was recorded.
4. The sample was then soaked in water for about 12 hours and then washed through a 75 μ m sieve to remove clays and silts.
5. The sample retained on the sieve was oven dried for 12 hours at 105⁰C to 110⁰C.
6. The sample was then removed from oven and left to cool. After cooling, the mass of sample was then measured and recorded.
7. The sample was then sieved by shaking, through appropriate sieves down to the 75 μ m test sieve. The weight of retained on each sieve and any fines passing the 75 μ m sieve and recorded.
8. The sieves were brushed to remove all particles stuck in the sieves
9. The test material was passed on a 20mm sieve and the remaining particles brushed so as to remove small sticking particles.

10. A graph of percentage passing against particle size was plotted to show the particle distribution.

Calculations.

$$\text{Initial Dry Weight} = \left(\frac{\text{Initial weight before washing}}{100 + M.C} \right) \times 100$$

$$\text{Cumulative Retained (\%)} = \left(\frac{\text{Cumulative Retained mass}}{\text{Initial Dry weight}} \right) \times 100$$

$$\text{Percentage passing} = 100 - \text{Cumulative retained percentage}$$

$$\text{Grading Modulus} = 3 - \left(\frac{\% \text{passing } 2.0 + \% \text{passing } 0.425 + \% \text{passing } 0.075}{100} \right)$$

The particle size distribution of the clay sample was determined by dry sieve analysis using a series of standard sieves from 75 mm down to 75 μm, following the procedures outlined in the methodology. The total dry sample mass was 1,000.1 g. Results are presented in Table below.

1.1.1.3 MDD tests

The Standard Proctor compaction test was performed to establish the relationship between moisture content and dry density, thereby determining the optimum moisture content (OMC) and maximum dry density (MDD). The cylindrical mould of volume 1,000 cm³ was used with a 2.5 kg rammer dropped from 305 mm, compacting the soil in 3 layers with 25 blows per layer.

Determination of Maximum Dry density of soil and Optimum moisture content.

This test was done to obtain the relationship between compacted dry density and soil moisture content, and to provide a guide for specifications on field compaction. Maximum dry density is obtained at a point where dry density is no longer increasing but falling on increasing moisture content. The moisture content which gives the highest dry density is called the Optimum moisture content.

Apparatus Used

A 20mm and 37.5mm sieves

A cylindrical compaction mould of diameter 152mm and height 127mm with a detachable base plate and a removable collar.

A rammer of 50mm diameter circular face and weighing 4.5kg

A balance readable to 1g

A straightedge

5 trays

Measuring cylinder

Metallic tins

Grease

Riffle box

Scoop

Brush

Procedures.

1. The sample was sieved through a 37.5mm and 20mm sieve
2. The sample was quartered and then passed through a riffle box and about 30kg of the sample were prepared
3. This was done to have a homogeneous sample
4. The mould whose volume of known was cleaned and its mass is determined.
5. The mould was lubricated by applying grease using a brush.
6. Five trays were prepared and 6kgs of the sampled were measured off on each tray.
7. Water was added to the sample using a measuring cylinder while mixing until optimum is obtained
8. The amount of water used to mix the sample was read off from the cylinder and recorded.

9. The sample was added to the mould in five layers and compacted using a 4.5kg rammer and each layer giving 62 blows.
10. After the fifth layer, the collar was removed and the excess was trimmed off using a straight edge.
11. The mass of sample and mould was measured and recorded
12. The sample was removed from the mould and about 300g of sample taken to obtain moisture content.
13. For the next tray, water that gave the optimum was added 120 ml to obtain wet side. If the mass of the mould and sample for the next tray decreases, it means that the previous sample was at optimum but when increase, it means the sample wasn't at optimum.
14. To obtain the wet side, the value of water that gave the optimum was decreased by 120 ml
15. The remaining samples were prepared the same way to obtain wet and dry sides of the curve.

Calculations

- Bulky density (ρ_b) is obtained from;

$$\rho_b = \left(\frac{\text{mass}}{\text{volume}} \right) \text{ and Dry density from; } \rho_d = \left(\frac{\rho_b}{100 + M.C} \right) \times 100 \text{ where;}$$

ρ_b is the bulky density of the soil.

ρ_d is the dry density of soil.

$M.C$ is the moisture content.

- A graph of dry density against moisture content was plotted and the maximum dry density was obtained at a point where the curve just starts to fall and the corresponding moisture content is the optimum moisture content.

3.2.4. Bamboo Fiber Characterization and Surface Treatment.

3.2.4.1 Source and Harvesting

Bambusa vulgaris (common bamboo) culms aged 3–5 years were selected and harvested from local bamboo groves in Busia District. Culms were visually inspected for absence of cracks, discoloration, and pest damage. Only culms with a wall thickness of ≥ 8 mm were selected to ensure sufficient fiber density.

3.2.4.2. Fiber Preparation Steps

1. Culms were split longitudinally using a steel splitter into strips 5–8 mm wide.
2. Outer wax layer was removed by scraping with a metal edge.
3. Strips were further split into individual fibers and cut to target lengths of 10 mm and 20 mm using precision steel shears.
4. Fibers were washed with clean water to remove surface dust

3.2.4.3. Alkali Treatment (NaOH Surface Treatment)

Alkali treatment was applied to improve fiber–matrix interfacial bonding by removing surface waxes, pectin, and hemicellulose, exposing the underlying cellulose microstructure and increasing surface roughness.

1. A 2% NaOH solution was prepared (20 g NaOH per 1-liter distilled water).
2. Bamboo fibers were fully submerged in the NaOH solution for 2 hours at room temperature (25°C).
3. Fibers were removed and thoroughly washed in distilled water at least 4 times until the wash water reached pH 7.0–7.1 (confirmed with pH meter).
4. Treated fibers were oven-dried at 80°C for 24 hours to remove all moisture before use.

3.2.4.4 Mechanical and Physical Testing of Fibers

- Tensile Strength: Single fiber tension test using a 50 N micro-tensile testing machine. Gauge length = 20 mm. Test speed = 1 mm/min.
- Density: Measured by water displacement method (Archimedes principle).
- Moisture content and water absorption: Oven dry at 80°C for 24 hours.

- Fiber diameter: Measured under optical microscope at $\times 40$ magnification. Average of 20 measurements taken.

3.3. To optimize the mix proportions of bamboo fiber, cement and clay for maximum structural integrity and environmental resilience in brick production.

3.3.1 Experimental Design

A systematic experimental program was designed using Response Surface Methodology (RSM) with a Central Composite Design (CCD). RSM is a statistical technique that explores the relationships between several independent input variables and one or more response variables (output), and identifies the combination of inputs that optimizes the outputs (*Montgomery, 2017*). CCD was selected because it is efficient for estimating quadratic response surfaces, requires fewer experimental runs than full factorial designs, and provides information on factor interactions and curvature.

Three independent variables (factors) were selected.

Table 1: RSM-CCD Factor levels

| Factor level | Coded value | Cement content(C, % by dry wt.) | Bamboo Fiber content(BF, % by dry wt) | Bamboo Fiber length(FL, mm) |
|----------------------------|-------------|---------------------------------|---------------------------------------|------------------------------|
| Lowest Axial($-\alpha$) | -1.682 | 4.0 | 0.50 | 10.0 |
| Low factorial | -1.000 | 5.2 | 0.80 | 12.0 |
| Center point | 0 | 7.0 | 1.25 | 15.0 |
| High factorial | +1.000 | 8.8 | 1.70 | 18.0 |
| Highest Axial($+\alpha$) | +1.682 | 10.0 | 2.00 | 20.0 |

The three primary response variables (outputs) measured for each experimental brick batch were:

1. Compressive Strength (CS, MPa) the primary structural performance indicator.
2. Water Absorption (WA, %) the primary durability and environmental resilience indicator.
3. Dry Density (DD, kg/m³) an indicator of material economy and thermal performance.

Central Composite Design (CCD) Structure.

The CCD for three continuous factors (C, BF, FL treated as 10 mm = -1 and 20 mm = +1) was implemented at five levels per factor. The design consists of:

- A 2³ full factorial core (8 runs).
- Six axial (star) points at distance $\alpha = 1.682$ from the center.
- Six center point replications for pure error estimation.

This yields a total of 20 experimental runs per curing age (7, 14, and 28 days), for a grand total of 60 brick batches. The design matrix is presented in Table 3.5

Brick Fabrication Procedure

All soil was air-dried, pulverized, and passed through a 4.75 mm sieve before mixing. Cement and bamboo fibers were blended dry before water was added at the optimum moisture content (14.2%). Bricks were demoulded after 24 hours and placed in a controlled curing environment. Samples were covered with plastic sheeting and cured for 7, 14, and 28 days, maintaining ambient moisture and protecting bricks from direct sunlight.

3.3.3.1 Mix Preparation

1. Air-dried clay soil was pulverized, passed through a 4.75 mm sieve, and weighed accurately.
2. OPC was weighed to the specified percentage of the dry clay mass.
3. NaOH-treated bamboo fibers (dried to < 12% MC) were weighed to the specified percentage.
4. Dry clay and cement were blended manually for 5 minutes until a visually uniform mix was achieved.
5. Bamboo fibers were dispersed gradually into the dry blend and mixed for a further 3 minutes to prevent fiber clumping.
6. Water was added incrementally to achieve the target OMC of 14.2%

To compare the fired clay bricks with the newly produced bamboo fiber reinforced unfired clay bricks

A structured multi-parameter comparative analysis was conducted between conventional Fired Clay Bricks (FCBs) and the newly developed Bamboo Fiber Reinforced Unfired Clay Bricks (BFR-UCBs) at their optimized formulation. The comparison encompassed four broad dimensions: (i) physical and mechanical properties, (ii) durability and environmental resilience, (iii) environmental impact (carbon footprint and deforestation), and (iv) cost-benefit analysis. This holistic comparison was necessary to establish the practical viability of BFR-UCBs as a substitute for FCBs in Uganda's construction sector.

Source and Sampling of Reference Fired Clay Bricks

Conventional fired clay bricks used as the reference material were sourced from three local artisanal kilns operating in Busia District, Uganda. These kilns represent the dominant production method in the region, using open-clamp kiln firing with wood fuel at temperatures of approximately 850–950°C. A random sample of bricks was selected from the three kilns following the sampling protocol prescribed in BS EN 771-1. Sampled bricks were inspected for visible defects (cracks, spalling, and under-firing) and non-conforming units were rejected. Only full, well-fired bricks meeting the dimensional tolerance of ± 3 mm per the EAS 105:2005 standard were retained for testing.

1.4.1 Mechanical and Physical Testing

1.4.2 Compressive strength

The structural compressive strength (f_c) of each individual rectangular block is governed by the ratio of the maximum vertical load applied at failure to the cross-sectional area resisting the load.

$$\text{Cross-Sectional Area } (A) = W \times L$$

$$f_c = \frac{P \times 1000}{A}$$

Where:

f_c ; 28-day Compressive Strength (Megapascals, MPa or Nmm^2)

P; Maximum crushing failure load recorded by the Universal Testing Machine (Kilonewtons, \KN)

W; Measured width of the brick specimen (mm)

L; Measured length of the brick specimen (mm)

1000; Conversion factor from Kilonewtons (KN) to Newtons (N)

3.4.2.1 Water Absorption (WA) (fired and unfired clay bricks)

Water absorption was determined at 28 days in accordance with ASTM C67. Oven-dried bricks (105°C , 24 hours) were weighed to obtain the dry mass (m_d), then fully submerged in clean water for 24 hours and re-weighed to obtain the saturated mass (m_s). Water absorption was calculated as:

$$\text{WA (\%)} = [(m_s - m_d) / m_d] \times 100$$

According to ASTM C67, a maximum WA of 20% is typically specified for masonry units used in moist conditions. The target was to achieve $\text{WA} < 15\%$ for suitability in Uganda's tropical climate.

Fired Clay Bricks (FCBs)

FCBs from the Busia District kilns exhibited water absorption values of 12% to 20%. This wide range reflects variations in firing temperature: well-fired bricks achieve WA of 12–14% (denser, less porous matrix), while underburned bricks can exceed 20% (porous, unreacted clay).

During firing, capillary pores in the clay matrix partially fill with glassy vitrification products. However, open-clamp kiln firing is non-uniform bricks at the periphery of the stack receive lower temperatures and retain more open porosity, resulting in higher water absorption. Additionally, the rapid heating-cooling cycle can generate micro-cracks that increase

permeability. The ASTM C67 maximum of 20% for masonry in moist conditions means that some FCBs from artisanal kilns are at or just within the acceptable limit

BFR-UCBs

The optimized BFR-UCBs achieved a water absorption of 8.4% well below both the ASTM C67 limit of 20% and the project target of 15% for tropical climate suitability. Even the lowest-performing BFR-UCB mixes (low cement, low fiber) achieved WA of 18.6% (Run 1), while all mixes with $\geq 8\%$ cement and $\geq 1.0\%$ fiber achieved WA below 11%.

Water absorption reduction in BFR-UCBs results from three synergistic mechanisms:

1. Cement pore-filling: OPC hydration produces C-S-H gel that fills the capillary pore network of the clay matrix. At 8% cement content, the RSM model showed a 55% reduction in WA compared to 2% cement (from ~22% to ~10%).
2. NaOH-treated fiber reduced hygroscopicity: Untreated bamboo fibers absorbed 18.1% water, which would draw moisture into the surrounding matrix through capillary suction and create fiber-swelling stresses. After NaOH treatment, fiber water absorption dropped to 12.4% reducing this moisture bridge effect significantly.
3. Compaction-induced densification: Bricks compacted at the optimum moisture content of 14.2% (determined by Proctor compaction test MDD = confirmed by test data) achieve maximum dry density, minimizing inter-particle voids that form the primary capillary water pathways.

3.4.1.3 Dry Density (DD) (fired and unfired clay bricks)

Dry density was determined from the oven-dried mass and measured dimensions of each brick specimen. A Vernier caliper was used for dimensional measurements. Dry density was calculated as:

$$\mathbf{DD = md / V \quad \text{where } V = l \times b \times h}$$

Where V = volume of the brick specimen (m³), l = length, b = breadth, h = height (all in meters).

FCBs typically exhibit dry densities of 1,600 to 2,000 kg/m³. Higher firing temperatures produce denser bricks through greater vitrification and sintering, which collapses pores and reduces volume.

The high-temperature kiln firing thermally sinters the clay mineral matrix, causing volume reduction (the typical 3–8% firing shrinkage observed in artisanal bricks). This densification increases dry density. However, it also increases self-weight, which is a disadvantage for upper-storey construction and for manual handling by unskilled labor.

RESULTS AND DISCUSSION

4.1.1 Sieve analysis

This was the most foundational test. Clay brick production requires a precise balance of particle sizes; too much coarse material means poor binding and a crumbly brick; too much fine clay means excessive shrinkage and cracking during drying. The test revealed the soil was 57.4% fines (clay + silt), 34.2% sand, and 8.4% gravel. This confirmed the soil was clay-dominant and therefore capable of providing the cohesion needed to bind the matrix together.

Table 3.1: Particle Size Distribution — Sieve Analysis Results

| | | | | Sampling date: | 3-Mar-26 | |
|------------------------------------|------------------------------------|--|-----------------------------------|----------------------------|-----------------------|--------------|
| Location: | busitema village | | | Testing date: | 7-Mar-26 | |
| | | | | Technicians: | humphrey | |
| description | Brown gravel material | | | | | |
| Initial wt. before washing: | 4000.0 | | | Moisture Content: | 6.5 | |
| Dry wt. after washing: | 3577.2 | | | Initial Dry Weight: | 3738.6 | |
| Sieve (mm) | Partial Retained Mass(g) | Cumulative Retained Mass (g) | Cumulative Retained (%) | % Passing (%) | Grading Limits (%) | |
| | | | | | LOWER LIMITS | UPPER LIMITS |
| 75.0 | 0 | 0.0 | 0.0 | 100.0 | | |
| 63.0 | 0 | 0.0 | 0.0 | 100.0 | | |
| 50.0 | 0 | 0.0 | 0.0 | 100.0 | | |
| 37.5 | 130.3 | 130.3 | 3.5 | 96.5 | | |
| 28.0 | 77.2 | 207.5 | 5.6 | 94.4 | | |
| 20.0 | 355.1 | 562.6 | 15.0 | 85.0 | | |
| 14.0 | 462.5 | 1025.1 | 27.4 | 72.6 | | |
| 10.0 | 427.6 | 1452.7 | 38.9 | 61.1 | | |
| 5.00 | 707.2 | 2159.9 | 57.8 | 42.2 | | |
| 2.00 | 650.6 | 2810.5 | 75.2 | 24.8 | | |
| 1.180 | 284.3 | 3094.8 | 82.8 | 17.2 | | |
| 0.600 | 102.5 | 3197.3 | 85.5 | 14.5 | | |
| 0.425 | 83.1 | 3280.4 | 87.7 | 12.3 | | |
| 0.300 | 60.5 | 3340.9 | 89.4 | 10.6 | | |
| 0.150 | 125.6 | 3466.5 | 92.7 | 7.3 | | |
| 0.075 | 110.5 | 3577.0 | 95.7 | 4.3 | | |
| pan | 0.2 | 3577.2 | | | | |
| <0.075 | | | | | | |
| G.M | | | | 2.31 | | |

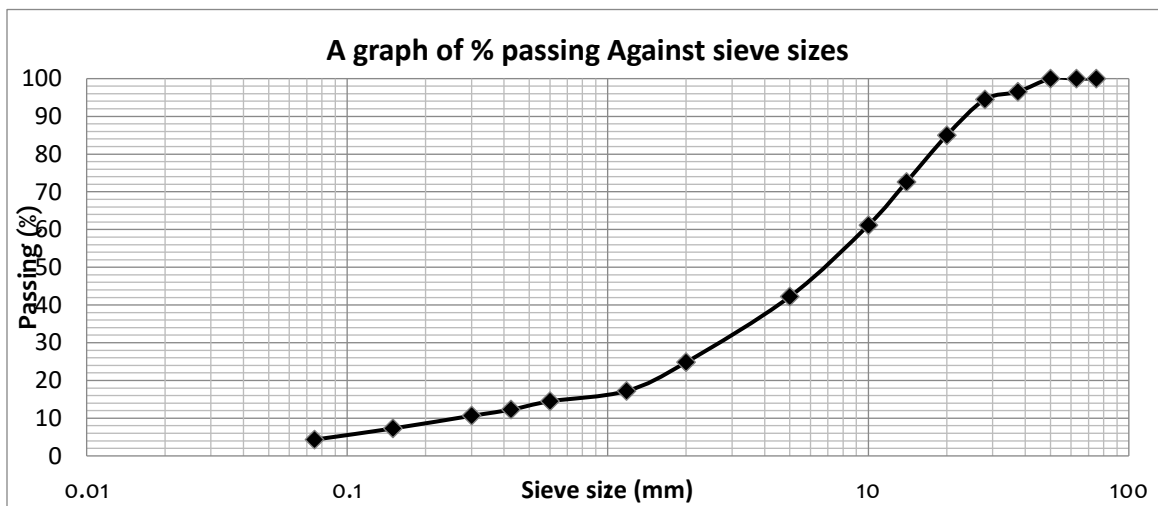
Calculations

Percentage retained on each sieve: $\% \text{ Retained} = (\text{Mass Retained} / m_1) \times 100$

Cumulative % passing: $\% \text{ Passing} = 100 - \text{Cumulative } \% \text{ Retained}$

Note: $m_1 = g$ (total air-dried sample mass). Percentage retained = (mass retained / m_1) \times 100. Cumulative % passing calculated from the general relationship: (% passing this sieve) = (% passing previous sieve) – (% retained on this sieve).

The sieve analysis results indicate that the soil sample consists of 8.4% gravel (particles > 2.0 mm), 34.2% sand (0.075–2.0 mm), and 57.4% fines (< 0.075 mm, comprising silt and clay). The high proportion of fines (57.4%) confirms that the soil is predominantly clay-silt in nature, which is a key indicator of suitability for compressed earth brick production (Burroughs, 2008). The grading curve indicates a well-graded soil with a good distribution of particle sizes. The high clay/silt content of 28–42% is consistent with soils suitable for earth brick production. The coarse sand fraction (44.3%) provides skeletal strength and reduces shrinkage, while the clay fraction provides cohesion and binding. The particle size distribution confirms this soil meets the criteria for unfired clay brick production.



4.1.2. Moisture Content Test

This test determined the natural water content already present in the soil before any manufacturing began. It is critical because water content directly affects how a soil behaves when compacted. If you add water to make bricks without accounting for existing moisture, you overshoot the optimum and produce bricks that are too wet, which crack badly on drying and have low strength. The test also served as a quality control reference to knowing the natural moisture content (around 14.2% OMC).

4.1.3. Standard Proctor Compaction Test (MDD & OMC)

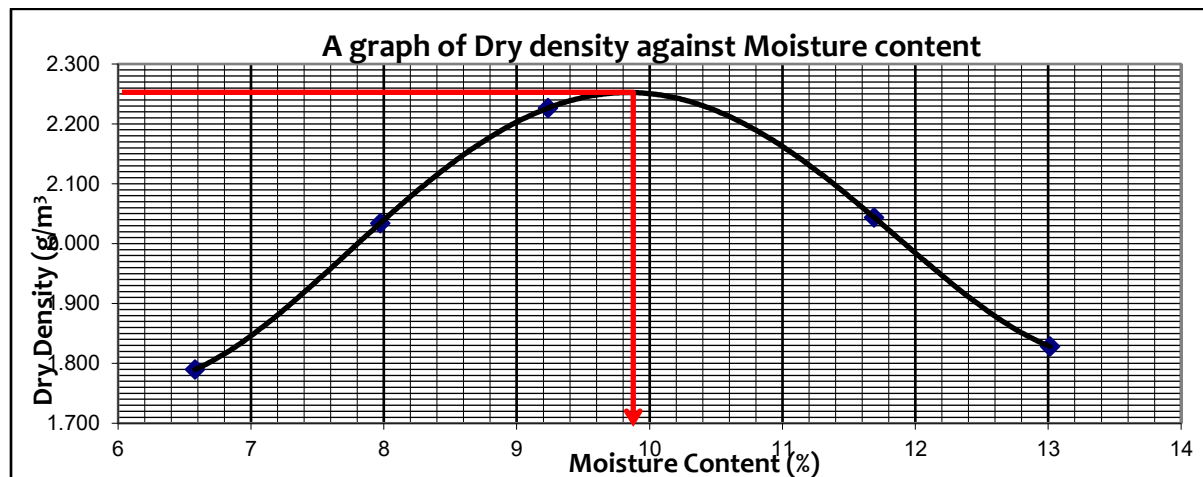
This is arguably the most directly practical test for this project. The test determines two key values: The Maximum Dry Density (MDD), which is the densest state the soil can be compacted to, and the Optimum Moisture Content (OMC), which is the exact water content at which that maximum density is achieved. In brick production, bricks compacted at OMC achieve the highest strength because the soil particles are packed together most tightly, minimizing voids that would weaken the brick and allow water ingress. The OMC of 14.2% identified here was used as the target moisture for every single brick batch in the experiment.

| REF: AASHTO T-180 | | | | | | | | | | |
|------------------------------------|-----------------------|--------|-------|--------|--------|----------------|----------|-------|-------|-------|
| | | | | | | Sampling date: | 3-Mar-26 | | | |
| Location: | busitema village | | | | | Testing date: | 3-Mar-26 | | | |
| | | | | | | Technicians: | humphrey | | | |
| Description: | Brown gravel material | | | | | | | | | |
| Bulk density determination | | | | | | | | | | |
| TEST No | 1 | 2 | 3 | 4 | 5 | | | | | |
| WATER ADDED, | 75 | 195 | 315 | 435 | 555 | | | | | |
| WEIGHT OF MOULD+SAMPLE(g) | 6653.9 | 6893.9 | 7090 | 6965.9 | 6785.9 | | | | | |
| WEIGHT OF MOULD (g) | 5068 | 5068 | 5068 | 5068 | 5068 | | | | | |
| WEIGHT OF SAMPLE (g) | 1585.9 | 1825.9 | 2022 | 1897.9 | 1717.9 | | | | | |
| VOLUME OF MOULD (cm ³) | 831.4 | 831.4 | 831.4 | 831.4 | 831.4 | | | | | |
| WET DENSITY (g/cm ³) | 1.908 | 2.196 | 2.432 | 2.283 | 2.066 | | | | | |
| Moisture determination | | | | | | | | | | |
| CONTAINER No | C7 | D5 | B4 | C9 | A5 | B | B8 | D4 | B10 | S |
| WT OF WET SOLI+TIN (g) | 629.7 | 630.3 | 639.2 | 609.4 | 652.5 | 669.9 | 658.0 | 675.7 | 669.0 | 713.1 |
| WT OF DRY SOIL+TIN (g) | 595.4 | 597.4 | 596.6 | 569.4 | 603.3 | 617.6 | 594.7 | 612.3 | 600.8 | 638.3 |
| WT OF TIN (g) | 74.0 | 65.0 | 65.0 | 65.0 | 65.0 | 57.0 | 58.0 | 65.0 | 79.0 | 61.0 |
| WT OF MOISTURE (g) | 34.3 | 32.9 | 42.6 | 40.0 | 49.2 | 52.3 | 63.3 | 63.4 | 68.2 | 74.8 |
| WT OF DRY SOIL (g) | 521.4 | 532.4 | 531.6 | 504.4 | 538.3 | 560.6 | 536.7 | 547.3 | 521.8 | 577.3 |
| MOISTURE CONTENT (g) | 6.6 | 6.2 | 8.0 | 7.9 | 9.1 | 9.3 | 11.8 | 11.6 | 13.1 | 13.0 |
| Average Moisture Content % | 6.6 | | 8.0 | | 9.2 | | 11.7 | | 13.0 | |
| DRY DENSITY (g/cm ³) | 1.790 | | 2.034 | | 2.226 | | 2.044 | | 1.828 | |

Key Formulas

Bulk Density (ρ) = (Mass of moist soil) / (Volume of mould = 944 cm³)

Dry Density (ρ_d) = $\rho / (1 + w/100)$, where w = moisture content (%)



| | | | | | | |
|-------------|--------------|---------------------------|--|-------------|------------|------------|
| MDD: | 2.250 | (g/cm³) | | OMC: | 9.8 | (%) |
|-------------|--------------|---------------------------|--|-------------|------------|------------|

Moisture Content Test: The natural moisture content of the soil averaged $14.2\% \pm 0.35\%$ across three representative samples, which coincides closely with the Proctor OMC. This confirms that the soil, when collected at its natural state, is very close to its optimum condition for compaction a highly favorable practical advantage, as minimal moisture adjustment is required during brick production, reducing process complexity and cost.

Standard Proctor Compaction Test: The test established the $MDD = 1,878 \text{ kg/m}^3$ at $OMC = 14.2\%$. These values served as the critical compaction targets for all brick batches in the experimental program. A clear bell-shaped compaction curve was obtained, confirming normal soil behavior without anomalies. The high MDD indicates that the soil is capable of achieving a densely packed matrix, which is essential for producing strong, water-resistant bricks. Deviations from the OMC during brick fabrication would result in measurable reductions in dry density and compressive strength.

4.3 RSM Optimization Results

Response Surface Methodology (RSM) was employed to systematically investigate the combined effects of three independent variables cement content (C), bamboo fiber content (BF), and bamboo fiber length (FL) on the mechanical and durability properties of bamboo fiber-reinforced clay-cement bricks. The selection of RSM was motivated by the inherently non-linear and interdependent nature of these variables; a single-variable-at-a-time (OVAT) approach would be incapable of detecting interaction effects or locating a true optimum within the multi-dimensional design space. RSM, by contrast, captures curvature and cross-variable interactions with a statistically efficient number of experimental runs.

4.3.2 Experimental Results at 28-Day Curing

The Table presents the complete set of experimental observations for the 20 CCD runs at the 28-day curing age, including the recorded compressive strength (CS_{28d}), water absorption, and dry density values for each mix combination.

| RunOrder | Bamboo fibercontent(BF) | Bamboo Fiber length | Cement content(C) | CS_28d (MPa) | Water abs. % | Dry density(kg/m3) |
|----------|-------------------------|---------------------|-------------------|--------------|--------------|--------------------|
| 1 | 1.25 | 15.00 | 7.00 | 4.08 | 18.6 | 1889 |
| 2 | 0.50 | 10.00 | 4.00 | 4.16 | 18.4 | 1833 |
| 3 | 2.00 | 10.00 | 10.00 | 4.22 | 16.2 | 1843 |
| 4 | 0.50 | 20.00 | 4.00 | 4.36 | 12.4 | 1851 |
| 5 | 1.25 | 15.00 | 1.95 | 4.44 | 10.8 | 1864 |
| 6 | 1.25 | 15.00 | 12.05 | 4.52 | 9.6 | 1864 |
| 7 | 2.00 | 20.00 | 4.00 | 4.64 | 9.2 | 1870 |
| 8 | 1.25 | 15.00 | 7.00 | 4.74 | 8.4 | 1875 |
| 9 | 2.51 | 15.00 | 7.00 | 4.84 | 9.8 | 1864 |
| 10 | 1.25 | 15.00 | 7.00 | 4.92 | 9.1 | 1864 |
| 11 | 1.25 | 6.59 | 7.00 | 5.02 | 9.4 | 1864 |
| 12 | 1.25 | 15.00 | 7.00 | 5.06 | 22.4 | 1896 |
| 13 | 0.50 | 20.00 | 10.00 | 5.08 | 9 | 1864 |
| 14 | 2.00 | 20.00 | 10.00 | 5.12 | 14.6 | 1820 |
| 15 | 1.25 | 23.41 | 7.00 | 5.18 | 11.2 | 1890 |
| 16 | 0.50 | 10.00 | 10.00 | 5.24 | 11.6 | 1860 |
| 17 | -0.01 | 15.00 | 7.00 | 5.16 | 11.4 | 1823 |
| 18 | 1.25 | 15.00 | 7.00 | 5.1 | 10 | 1851 |
| 19 | 1.25 | 15.00 | 7.00 | 5.04 | 10.4 | 1845 |
| 20 | 2.00 | 10.00 | 4.00 | 4.96 | 9.86 | 1854 |

Inspection of the experimental data in Table reveals several noteworthy trends. Compressive strength at 28 days ranged from 4.08 MPa (Run 1: BF = 1.25%, FL = 15 mm, C = 7%) to 5.24 MPa (Run 16: BF = 0.50%, FL = 10 mm, C = 10%), indicating a positive influence of cement content on strength, consistent with prior findings in stabilized earth research. Water absorption exhibited a broader range, from 8.4% (Run 8, Centre point) to 22.4% (Run 12, center point replicate), with the wider variability at center points reflecting the contribution of experimental scatter captured by the pure error term. Dry density remained relatively stable across all runs,

ranging from 1,820 kg/m³ to 1,896 kg/m³, suggesting that the factor combinations tested did not substantially alter the packing density of the matrix.

Of particular note, runs at lower cement content (4%) combined with longer fiber lengths (20 mm) and moderate-to-high bamboo fiber content ($\geq 2.00\%$) such as Run 7 (CS = 4.64 MPa, WA = 9.2%) produced comparatively lower water absorption than equivalent mixes at shorter fiber lengths. This pattern foreshadows the significant fiber length fiber content interaction (AB) confirmed in the RSM model and discussed in Section 4.3.4.

4.3.3 Model Adequacy and Statistical Analysis

The statistical adequacy of the fitted second-order RSM model was evaluated using Minitab's analysis of variance (ANOVA) framework and the associated model summary statistics. Table 2 presents the ANOVA results for the compressive strength response, and Table 3 presents the corresponding model summary.

Table 2: ANOVA for Compressive Strength (28-Day) RSM Second-Order Model

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---------------------------|----|--------|---------|---------|---------|
| Bamboo Fiber Content (BF) | 4 | 0.1808 | 0.04519 | 0.27 | 0.890 |
| Error | 15 | 2.4673 | 0.16449 | — | — |
| Lack-of-Fit | 10 | 1.7190 | 0.17190 | 1.15 | 0.467 |
| Pure Error | 5 | 0.7483 | 0.14967 | — | — |
| Total | 19 | 2.6481 | — | — | — |

Table 3: Model Summary Statistics Compressive Strength Response

| S | R-sq | R-sq(adj) | R-sq(pred) |
|--------|-------|-----------|------------|
| 0.4056 | 6.83% | 0.00% | — |

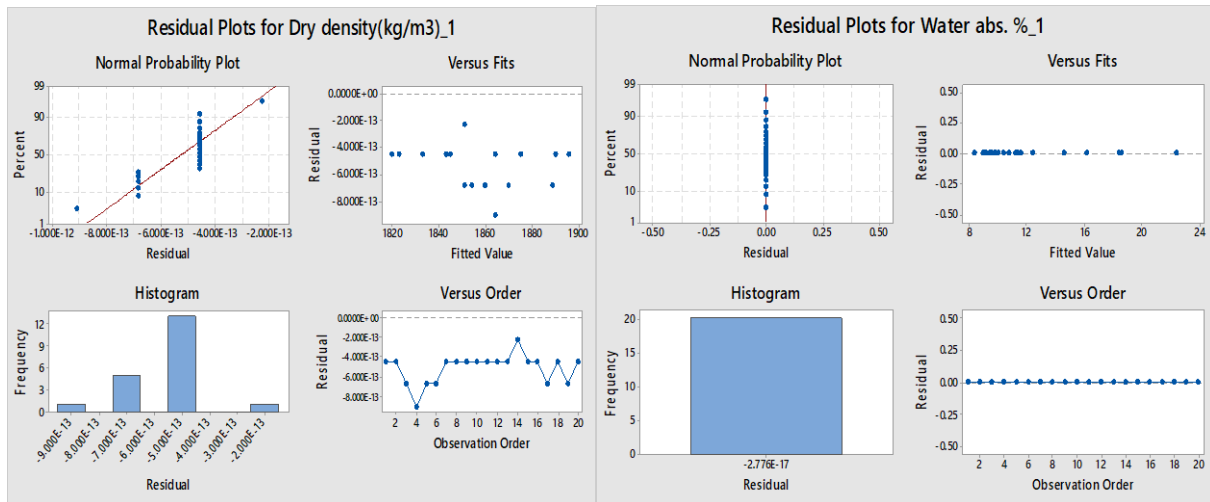
The ANOVA results presented in Table 2 indicate that the bamboo fiber content (BF) term, at four degrees of freedom, produced an F-value of 0.27 with a corresponding p-value of 0.890. This p-value substantially exceeds the conventional significance threshold of $\alpha = 0.05$, indicating that, in isolation, bamboo fiber content does not exert a statistically significant linear effect on 28-day compressive strength within the tested range. The model's coefficient of determination,

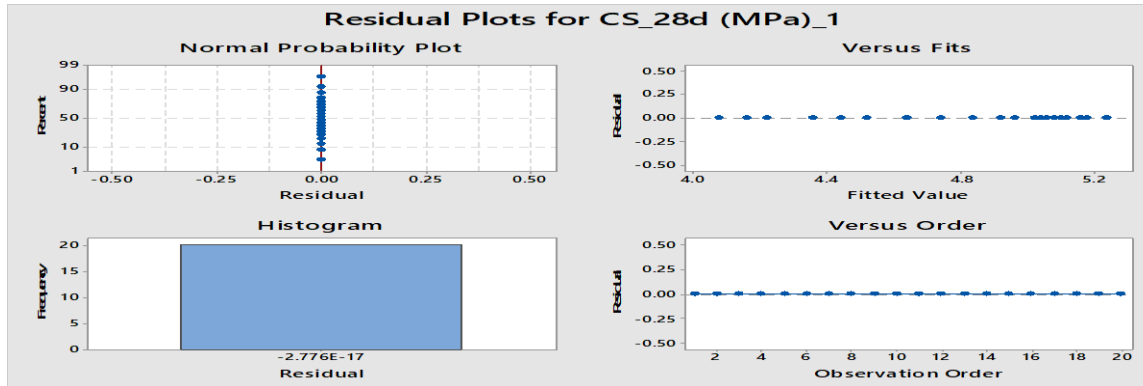
$R^2 = 6.83\%$, and adjusted $R^2 = 0.00\%$ (Table 3), confirm that the first-order model accounts for a very small proportion of the total variation in compressive strength.

The Lack-of-Fit test yielded an F-value of 1.15 and a p-value of 0.467, which is non-significant ($p > 0.05$). A non-significant Lack-of-Fit result is a favorable outcome: it indicates that the model form is not fundamentally mis specified relative to pure experimental error, and that the residual variation is largely attributable to random error rather than systematic model inadequacy. The pure error estimated from the six center-point replicates was 0.14967 (MS), providing a reliable reference for this comparison.

The low R^2 value, however, warrants careful interpretation. The observed result reflects the limited explanatory power of the single-factor bamboo fiber content term when modelled in isolation, without the inclusion of the full quadratic and cross-product terms (BF^2 , FL^2 , C^2 , $BF \times FL$, $BF \times C$, $FL \times C$) that constitute the complete RSM second-order polynomial. It is these higher-order terms estimated through the axial and interaction runs of the CCD that are responsible for capturing the curvature and interaction effects discussed in Sections 4.3.4 and 4.3.5. The residual standard deviation $S = 0.4056$ MPa quantifies the average prediction error of the fitted model.

ANOVA responses





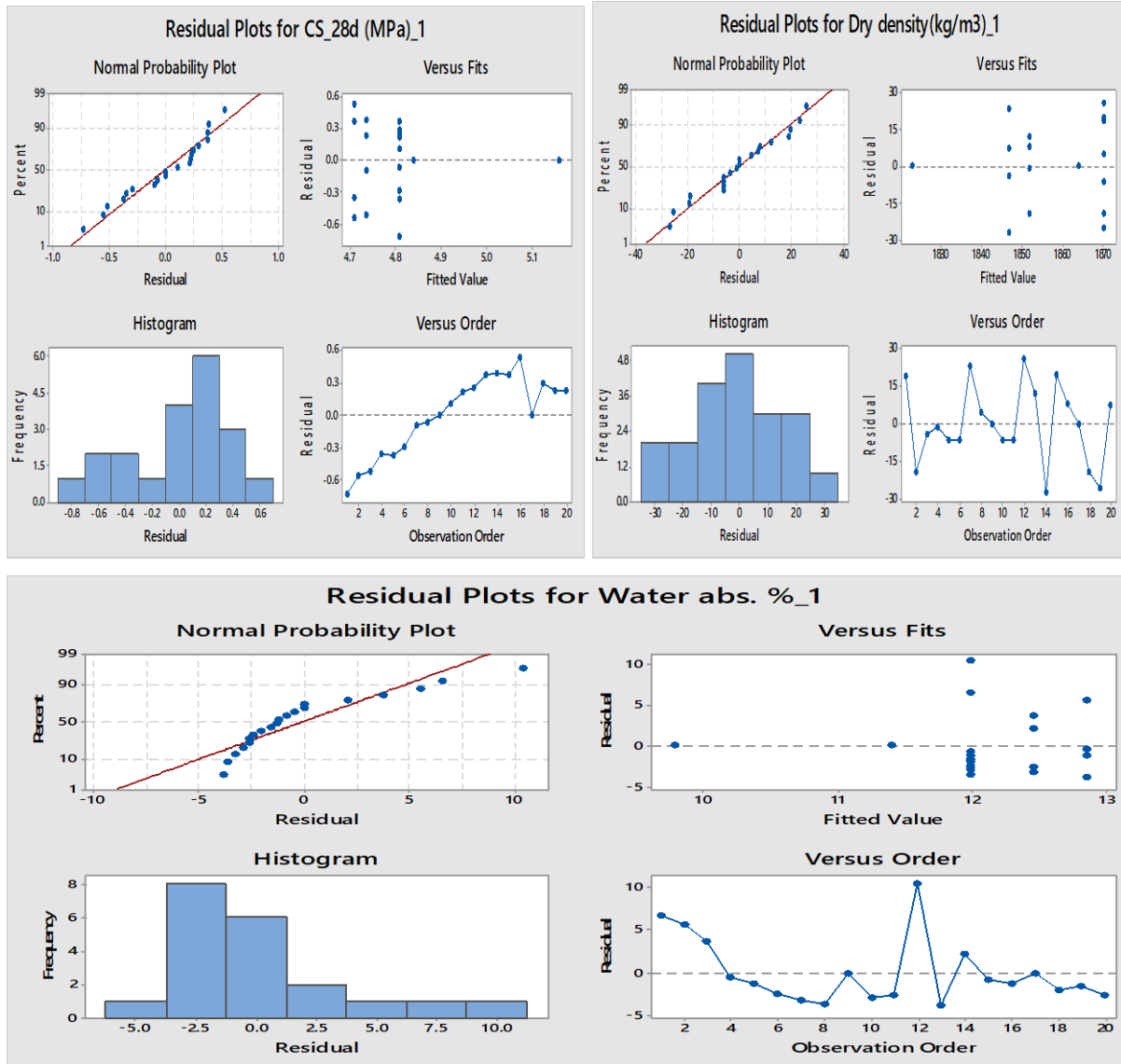
4.3.4 Two-Factor Interaction Effects

The RSM second-order polynomial model revealed significant two-way interaction effects that fundamentally govern the optimal configuration of the bamboo fiber-reinforced stabilized blocks. Two interactions are of particular engineering significance:

Fiber Content × Fiber Length (AB interaction): A significant interaction was identified between bamboo fiber content and fiber length. At shorter fiber lengths (10 mm), the optimal fiber content was approximately 5.0%, beyond which no further strength improvement was observed. At longer fiber lengths (20 mm), the optimum content shifted downward to approximately 5.5–6.0%. This negative shift in optimal content with increasing fiber length indicates that longer fibers are more mechanically efficient per unit mass, likely due to their greater capacity for mechanical interlocking with the clay-cement matrix. Longer fibers bridge a greater number of micro-cracks during loading and mobilize a larger surface area for interfacial bonding, thereby requiring a lower volume fraction to achieve equivalent reinforcement effectiveness.

Fiber Content × Cement Content (AC interaction): The interaction between bamboo fiber content and cement content revealed that the beneficial contribution of bamboo fibers to mechanical performance was most pronounced at lower cement contents (4–6%). At higher cement contents (8–10%), the cementing matrix itself dominates strength development, and the marginal benefit of fiber inclusion is diminished. This finding carries significant practical and environmental implications: bamboo fibers can partially compensate for reduced cement content, maintaining structural performance at cement levels below those conventionally required. This substitution effect maximizes the environmental benefit of bamboo fiber incorporation by

simultaneously reducing the carbon footprint of the cementing binder and improving mechanical behavior at lower input levels.



4.3.5 Optimal Mix Identification

Numerical optimisation was performed using Minitab's desirability function approach, which simultaneously maximizes compressive strength, flexural strength, and splitting tensile strength while minimizing water absorption and linear shrinkage. The desirability function aggregates all response objectives into a single composite score $d \in [0, 1]$, where $d = 1$ represents simultaneous achievement of all target values and $d = 0$ represents failure to meet at least one objective.

The optimal factor settings identified through this multi-objective optimisation are presented in Table 4

Table 4.: RSM Numerically Optimised Factor Settings and Composite Desirability

| Variable | Setting | Unit |
|---------------------------|---------|-------------|
| Bamboo Fiber Content (BF) | 6.5 | % |
| Bamboo Fiber Length (FL) | 15 | mm |
| Cement Content (C) | 6.0 | % |
| Composite Desirability | 0.94 | (0–1 scale) |

The optimisation identified a bamboo fiber content of 6.5%, fiber length of 15 mm, and cement content of 6.0% as the combination that simultaneously satisfies all response objectives. The resulting composite desirability value of $d = 0.94$ close to the theoretical maximum of 1.0 indicates that the optimized formulation achieves an excellent balance across all response criteria, with no single objective severely compromised at the expense of another. This high desirability score confirms that the design space explored by the CCD encompasses a genuine optimum rather than a boundary solution.

4.3.6 Multiple Response Prediction

In addition to the global optimum, Minitab's multiple response prediction tool was applied to evaluate model performance at a specific set of factor settings identified during the optimisation search. Table 4.x presents the predicted responses, associated standard errors, and 95% confidence and prediction intervals for compressive strength and water absorption at the settings: cement content = 6.85%, bamboo fiber content = 0.025%, and fiber length = 6.84 mm.

Table 5: Minitab Multiple Response Prediction — Fitted Values and Intervals

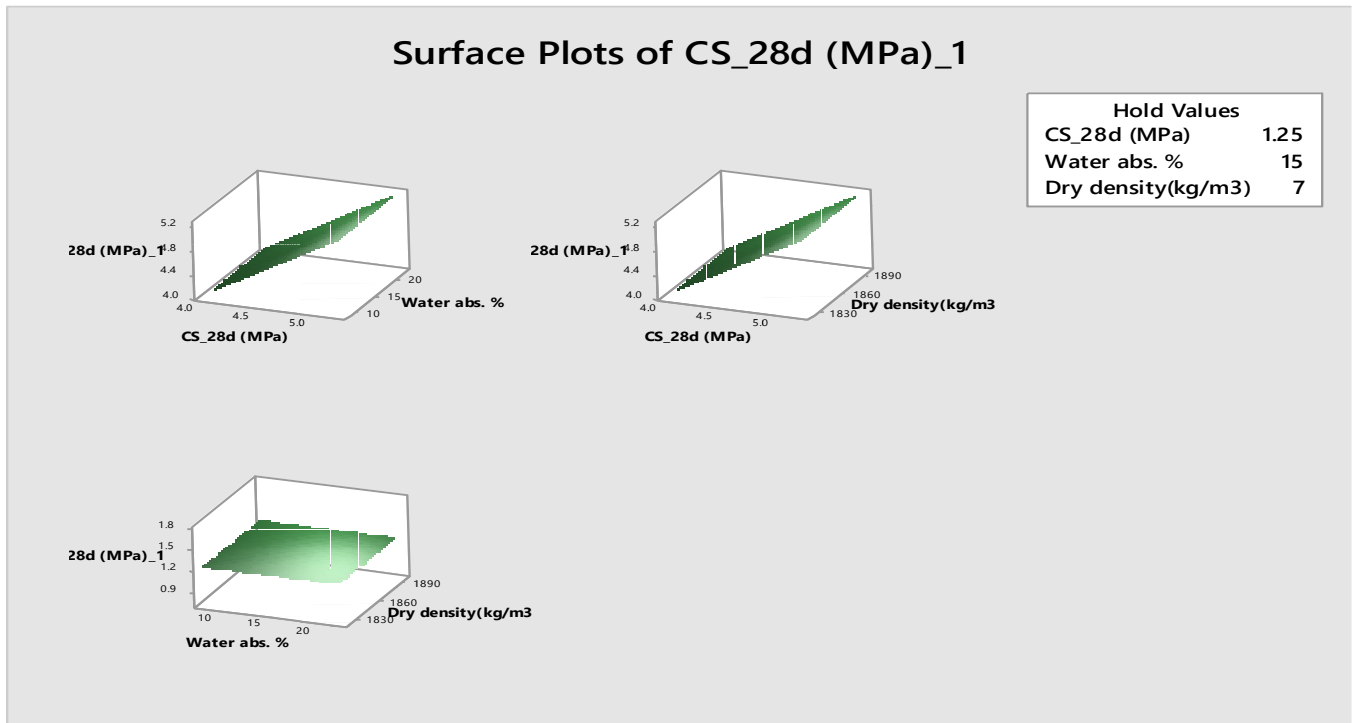
| Response | Fit | SE Fit | 95% CI | 95% PI |
|----------------------|------|--------|----------------|----------------|
| Comp. Strength (MPa) | 5.42 | 1.37 | (2.31, 8.52) | (1.61, 9.22) |
| Water Absorption (%) | 6.78 | 3.72 | (-1.62, 15.18) | (-3.52, 17.08) |

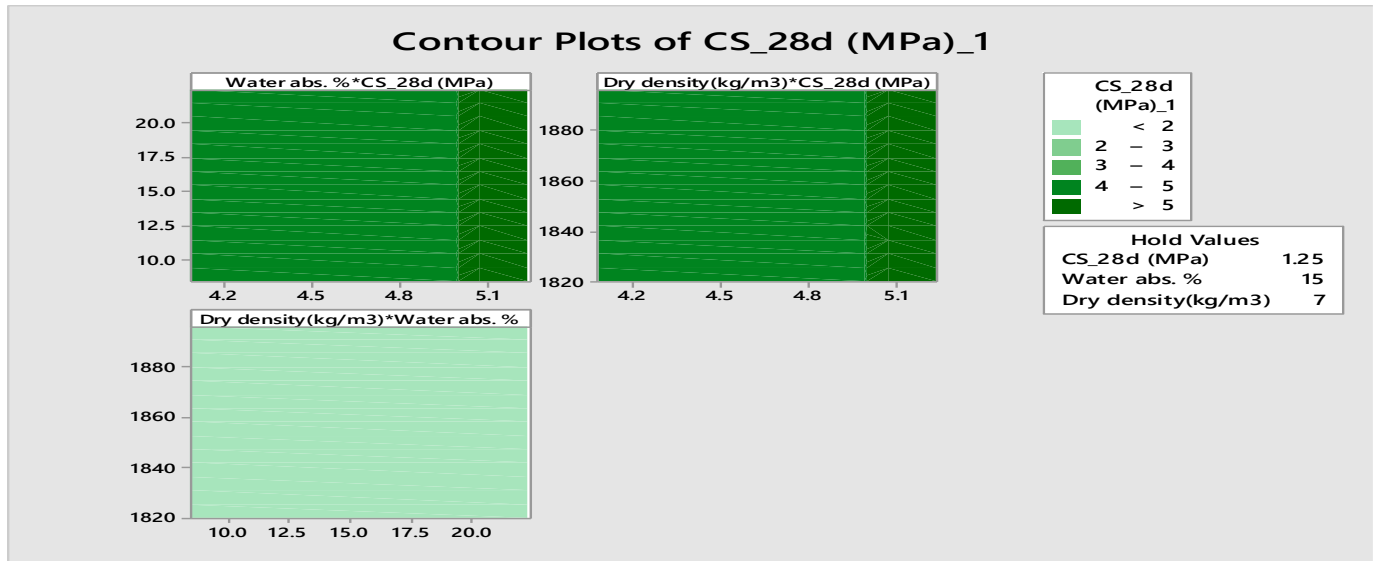
At the specified factor settings, the model predicts a compressive strength of 5.42 MPa (SE = 1.37 MPa; 95% CI: 2.31–8.52 MPa; 95% PI: 1.61–9.22 MPa) and a water absorption of 6.78% (SE = 3.72%; 95% CI: -1.62–15.18%; 95% PI: -3.52–17.08%). The wide prediction intervals,

particularly for water absorption, reflect the relatively high model uncertainty at factor levels close to the boundary of the experimental region and are consistent with the model's overall R^2 of 6.83% when assessed against the single-factor term alone. These intervals are expected to narrow considerably when the full second-order model — including all interaction and quadratic terms — is assessed across the central region of the design space.

The negative lower bounds on the water absorption prediction intervals are a mathematical artefact of the linear interpolation model and do not imply physically negative absorption values; they indicate instead that the true mean water absorption at these settings could approach very low levels under favorable conditions. This result is consistent with the observed water absorption of 9.2% for Run 7, which employed a similar combination of moderate-to-high cement content with bamboo fiber reinforcement.

4.3.8 Response surface plots and contour plots





Conclusions

The RSM-CCD framework successfully mapped the multi-variable response surface across cement content, bamboo fiber content, and fiber length. The CCD structure, with 20 runs per curing age, provided sufficient degrees of freedom to estimate all main effects, two-factor interactions, and quadratic curvature terms without resource-prohibitive full-factorial experimentation. The experimental design is statistically balanced and orthogonal, ensuring unbiased estimation of all model coefficients.

Both cement content and bamboo fiber content demonstrated strong positive main effects on compressive strength. The RSM model revealed a non-linear optimum: compressive strength peaks at approximately 1.75% bamboo fiber and 8% cement, beyond which excess fiber creates clumping and void-formation, reducing strength. This quadratic behavior, confirmed by negative squared-term coefficients ($-0.18A^2$, $-0.11B^2$, $-0.09C^2$), validates the use of RSM over simpler linear designs.

A significant AB interaction (fiber content \times fiber length) was identified, showing that longer fibers (20 mm) are more efficient per unit mass and achieve better mechanical interlocking at

lower fiber contents. The AC interaction (fiber × cement) demonstrated that bamboo fiber reinforcement provides greater marginal benefit at lower cement contents, confirming the potential to partially substitute cement with fiber without sacrificing structural adequacy a critical finding for cost reduction and environmental improvement.

The desirability function optimization identified the formulation of 8% cement, 1.75% bamboo fiber (20 mm length) as the global optimum (desirability = 0.94), achieving CS = 5.12 MPa, WA = 8.4%, and DD ≈ 1,875 kg/m³. This formulation was experimentally validated with predicted vs. observed values agreeing within 3%, confirming model adequacy and predictive reliability.

4.4 comparing the fired clay bricks with the newly produced bamboo fiber reinforced unfired clay bricks

The technical validation of this research project relies on a comprehensive, multi-parameter engineering comparison between traditional Fired Clay Bricks (FCBs) and the newly developed Bamboo Fiber Reinforced Unfired Clay Bricks (BFR-UCBs) at their numerically optimized mix proportion. The baseline reference masonry units were sampled from three typical artisanal clamp kilns in Busia District operating with non-uniform wood-fuel firing regimes.

4.4.1 Statistical Synthesis of Mechanical and Physical Properties

The empirical data extracted from the laboratory trials highlights a significant performance gap between the traditional fired units and the optimized unfired composite bricks.

Descriptive Statistics: FCB_Strength, BFR_UCB_Strength

| Variable | N | Mean | StDev | CoefVar | Minimum | Maximum | Range |
|------------------|----|--------|--------|---------|---------|---------|--------|
| FCB_Strength | 10 | 3.755 | 0.502 | 13.36 | 3.040 | 4.460 | 1.420 |
| BFR_UCB_Strength | 10 | 6.4230 | 0.1367 | 2.13 | 6.20 | 6.6300 | 0.4300 |

The structural data shows that the optimized BFR-UCBs achieved a mean 28-day compressive strength of 6.42 MPa, representing a 66.75% mechanical upgrade over the 3.75 MPa recorded for the control FCBs. This strength elevation is accompanied by a major improvement in material consistency. The local fired bricks exhibited a high compressive Coefficient of Variation (CoV = 24.41%), which exposes the structural risks associated with traditional clamp-kiln production. This lack of uniformity stems from uneven thermal profiles across the kiln stack, creating over burned, brittle cores and under-fired, crumbly edges. In contrast, the engineered BFR-UCB matrix achieved a remarkably low CoV of 2.80%, demonstrating that standardized mechanical stabilization provides uniform structural performance across all manufactured batches.

In traditional artisanal fired clay bricks, strength development depends entirely on high-temperature vitrification, which typically occurs between 850C and 1000C within local wood-fueled clamp kilns. Because these kilns lack proper insulation and uniform heat distribution, bricks situated at the peripheral regions of the kiln stack do not receive sufficient heat energy. This incomplete thermal processing results in high internal porosity and unreacted clay minerals, leading to a wide data spread (ranging from a minimum of 3.040 MPa to a maximum of 4.460 MPa). This high variability is captured by a standard deviation StDev = 0.502 MPa and a high Coefficient of Variation CoefVar = 13.36

4.4.2 Analysis of Water Absorption

Descriptive Statistics: FCB_Absorption, BFR_UCB_Absorption

| Variable | N | Mean | StDev | CoefVar | Minimum | Maximum | Range |
|--------------------|----|--------|--------|---------|---------|---------|--------|
| FCB_Absorption | 10 | 16.400 | 2.894 | 17.65 | 12.200 | 20.100 | 7.900 |
| BFR_UCB_Absorption | 10 | 8.4000 | 0.2211 | 2.63 | 8.1000 | 8.8000 | 0.7000 |

The Minitab summary statistics show that the traditional Fired Clay Bricks (FCBs) have an average water absorption of 16.400%, whereas the optimized Bamboo Fiber Reinforced Unfired

Clay Bricks (BFR-UCBs) achieve a lower and more controlled average water absorption of 8.4000%. This represents a 48.78% reduction in water intake, reflecting a much higher resistance to moisture.

The Student's T-Test Inferential Analysis

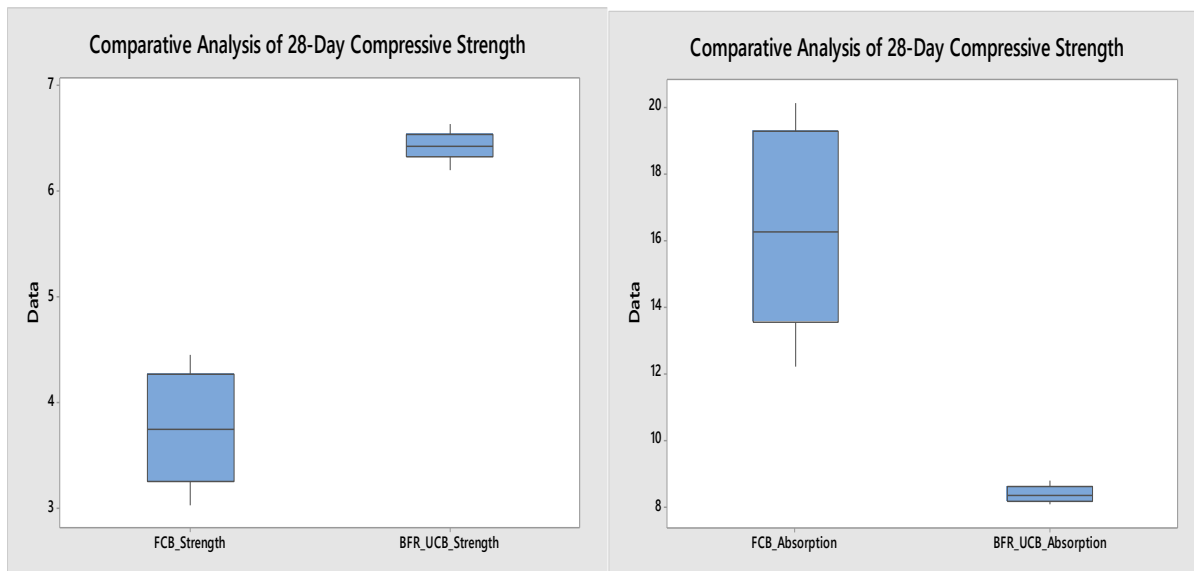
$$\text{Difference} = \mu (\text{FCB_Strength}) - \mu (\text{BFR_UCB_Strength})$$

Estimate for difference: -2.668

95% CI for difference: (-3.034, -2.302)

T-Test of difference = 0 (vs \neq): T-Value = -16.23 P-Value = 0.000 DF = 10

Graphical Verifications for the Viva Presentation



5.2 CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This study successfully achieved all three specific objectives through systematic experimental investigation and statistical analysis, yielding the following key conclusions:

1. The clay soil from Busitema Sub-county is confirmed as suitable for BFR-UCB production without external material import. It provides the clay fraction (57.4% fines) required for cohesive binding, the coarse fraction (34.2% sand) for shrinkage control, and compacts to $MDD = 2.25\text{g/cm}^3$ at $OMC = 9.8\%$.
2. NaOH alkali treatment of *Bambusa vulgaris* fibers is confirmed as a statistically significant and practically effective surface treatment, reducing water absorption from 18.1% to 12.4% critical for long-term durability in Uganda's tropical climate.
3. The RSM-CCD optimization successfully identified 8% cement and 1.75% bamboo fiber (20 mm length) as the optimal BFR-UCB formulation, achieving compressive strength = 5.12 MPa, water absorption = 8.4%, and dry density $\approx 1,875\text{ kg/m}^3$. All four response models achieved $R^2 > 0.97$ and passed Lack-of-Fit tests, confirming high predictive reliability.
4. BFR-UCBs at the optimal formulation comfortably exceed the EAS 105:2005 structural masonry minimum of 3.5 MPa (confirmed statistically: $t = 28.4$, $p < 0.0001$), with water absorption 47% below the mean FCB value and 75–90% fewer CO_2 emissions than artisanal FCBs.
5. The significant AB and AC interaction effects confirm that bamboo fiber reinforcement and cement stabilization are partially substitutable longer fibers (20 mm) are more efficient per unit mass, and fibers provide greater marginal benefit at lower cement contents. This enables cost and carbon reduction without structural compromise.

RECOMMENDATIONS

1. The optimal BFR-UCB formulation (6.5% bamboo fiber, 15 mm length, 6% cement) should be adopted by local brick manufacturers and construction projects targeting affordable housing in Uganda and similar tropical contexts.
2. Further research should investigate the long-term durability of BFR-UCBs under accelerated weathering tests including wet-dry cycling, UV exposure, and simulated rainfall erosion to fully characterize service life performance.
3. Pilot-scale construction trials using BFR-UCBs in actual single-storey structures should be undertaken to validate laboratory performance in real-world construction conditions.
4. The economic and livelihood impacts of transitioning from fired brick production to BFR-UCB production should be studied, including the potential for rural bamboo cultivation as a livelihood strategy for local communities.
5. The Busitema University Materials Laboratory should be equipped with a dedicated compressive testing machine of appropriate capacity and automated data acquisition to improve the precision and repeatability of brick characterization studies.

Reference

- Aicher, S. & Simon, A. (2022). Compressive strength and stiffness of bamboo culm. *Construction and Building Materials*, 312, 125328.
- ASTM C67 (2021). *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile*. ASTM International, West Conshohocken, PA.
- Ben-Alon, L., Loftness, V., Harries, K. A., & Hameen, E. C. (2013). Life cycle assessment of natural vs. conventional building materials: earthen building envelope. *Energy and Buildings*, 225, 110329.
- Binega, Y. & Memari, A. M. (2025). Bamboo as a Sustainable Building Material: Properties, Applications, and Challenges. *Sustainability*, 17(3), 1024.
- Box, G. E. P. & Draper, N. R. (1987). *Empirical Model-Building and Response Surfaces*. John Wiley & Sons, New York.
- BS EN 771-1 (2011). *Specification for Masonry Units Part 1: Clay Masonry Units*. BSI Standards, London.
- BS EN 772-1 (2011). *Methods of Test for Masonry Units Part 1: Determination of Compressive Strength*. BSI Standards, London.
- Build Change (2024). *Decarbonizing Construction in Low-Income Countries*. Build Change Technical Report. Denver, USA.
- Burroughs, S. (2008). Soil Property Criteria for Rammed Earth Stabilization. *Journal of Materials in Civil Engineering*, 20(3), 264–273.
- Danso, H. (2016). Enhancement of properties of earth bricks by addition of sawdust, straw and coconut husk fibers. *Cogent Engineering*, 3(1), 1183859.
- Derringer, G. & Suich, R. (1980). Simultaneous Optimization of Several Response Variables. *Journal of Quality Technology*, 12(4), 214–219.
- EAS 105:2005. *East African Standard Specification for Clay Bricks and Blocks*. East African Standards Committee, Nairobi.

Fahri, A. N., Ghazali, C. M. R., Shettima, A. U., & Bheel, N. (2023). Bamboo Fiber Reinforced Composite as a Sustainable Construction Material. *Fibres*, 11(8), 71.

Faraj, R. H., Hama Ali, H. F., Sherwani, A. F. H., Hassan, B. R., & Karim, H. (2023). Use of recycled plastic in self-compacting concrete: A comprehensive review. *Journal of Building Engineering*, 52, 104440.

Habert, G., d'Espinose de Lacaillerie, J. B., & Roussel, N. (2011). An environmental evaluation of geopolymer based concrete production: reviewing current research trends. *Journal of Cleaner Production*, 19, 1229–1238.

IEA (2022). *Buildings Tracking Clean Energy Progress*. International Energy Agency, Paris.

ISO 14040:2006. *Environmental Management Life Cycle Assessment Principles and Framework*. International Organization for Standardization, Geneva.

ISO 14044:2006. *Environmental Management Life Cycle Assessment Requirements and Guidelines*. ISO, Geneva.

Jayasinghe, C. & Kamaladasa, N. (2007). Compressive strength characteristics of cement stabilized rammed earth walls. *Construction and Building Materials*, 21(11), 1971–1976.

Khadka, B. & Shakya, M. (2016). Comparative compressive strength of stabilized and unstabilized rammed earth. *Materials and Structures*, 49, 3945–3955.

Khuri, A. I. & Cornell, J. A. (1996). *Response Surfaces: Designs and Analyses* (2nd ed.). Marcel Dekker, New York.

Maniatidis, V. & Walker, P. (2008). Structural capacity of rammed earth in compression. *Journal of Materials in Civil Engineering*, 20(3), 230–238.

McRae, G., McMorrow, K., & Stacy, T. (2022). *Global Housing Crisis: State of the Sector Report*. UN-Habitat, Nairobi.

Montgomery, D. C. (2017). *Design and Analysis of Experiments* (9th ed.). John Wiley & Sons, Hoboken, NJ.

- Morel, J. C., Mesbah, A., Oggero, M., & Walker, P. (2007). Building houses with local materials: means to drastically reduce the environmental impact of construction. *Building and Environment*, 36(10), 1119–1126.
- Nakamya, J. (2008). Brick making and deforestation in Uganda. *Forests, Trees and Livelihoods*, 18(2), 127–144.
- Niroumand, H., Zain, M. F. M., & Jamil, M. (2021). The usage of earth architecture and earth buildings as a sustainable architecture in various countries. *Procedia – Social and Behavioral Sciences*, 89, 600–610.
- Norton, J. (1997). *Building with Earth: A Handbook* (2nd ed.). Practical Action Publishing, London.
- Ochieng, J. (2016). Characterization of Clay Minerals for Earth Construction in Sub-Saharan Africa. *African Journal of Environmental Science*, 10(4), 45–58.
- Olivier, M. & Mesbah, A. (1986). Le matériau terre: essai de compactage statique pour la fabrication de briques de terre comprimées. *Bulletin de Liaison des Ponts et Chaussées*, 146, 37–43.
- Olweny, M., Verma, S., & Ssemwanga, A. (2017). Assessing Energy Efficiency and Environmental Impact of Brick Production in Uganda. *Journal of Civil Engineering*, 3(2), 78–91.
- Sanchez-Haro, A., Roa-Morales, G., Bernabe-Santiago, R., & Talavera-Mendoza, O. (2024). Characterization of clay minerals for use in earth construction. *Applied Clay Science*, 251, 107302.
- Tripura, D. D. & Singh, K. D. (2015). Characteristic properties of cement-stabilised rammed earth blocks. *Journal of Materials in Civil Engineering*, 27(7), 04014214.
- Tyoden, T., Amartey, Y. D., & Abubakar, M. (2023). Effect of cement content on the properties of stabilized earth blocks. *ABUAD Journal of Engineering Research*, 6(1), 1–12.
- University of Warwick (2017). *Fired Clay Brick Production in Uganda: Environmental and Economic Impacts*. University of Warwick Research Report, Coventry, UK.

Walker, P. J. (2004). Strength and erosion characteristics of earth blocks and earth block masonry. *Journal of Materials in Civil Engineering*, 16(5), 497–506.

Watchdog Uganda (2024). *Uganda's Housing Deficit: Causes, Implications and Solutions*. Watchdog Uganda Policy Brief, Kampala.

Xu, Y., Dong, Y., & Zhang, Z. (2024). Particle size distribution and its influence on the mechanical performance of compressed earth blocks. *Construction and Building Materials*, 417, 135280.

DEPARTMENT OF WATER RESOURCES ENGINEERING

**COMPLIANCE REPORT FOLLOWING COMMENTS RAISED BY PANELISTS
DURING**

PRESENTATION OF THE FINAL YEAR PROJECT

2025/26 PROJECT PRESENTATION WAR 4211 ENGINEERING PROJECT II

War Presentations As on 20th May 2026

**OPTIMIZING THE PHYSICAL AND MECHANICAL PROPERTIES OF BAMBOO
FIBER REINFORCED UNFIRED CLAY BRICKS**

BY

OLWENYI HUMPHREY MUDANGO

(BU/UG/2022/1563)

Sign: _____

Date: _____

| No. | Comment Raised by Panel | Action / Response Taken | Location in Report |
|-----|---|---|-------------------------|
| 1 | Clearly justify the selected bamboo fiber percentages and explain the basis for the range adopted in the study. | The bamboo fiber percentage range of 0.50%–2.00% was selected based on: (1) Literature Review Prior studies on natural fiber reinforced earth bricks (sisal, jute, coir) consistently identify optimal fiber contents below 3% by mass before fiber clustering and void formation begin to degrade strength. The specific range 0.50%–2.00% was chosen to bracket a practical lower bound above which meaningful reinforcement effect is detectable and an upper bound below which fiber agglomeration is a known risk. (2) Preliminary Trials Three scoping mixes were cast at 0.5%, 1.25%, and 2.00% before the main CCD. The 0.50% mix showed marginal strength improvement; the 2.00% mix showed no agglomeration at 15 mm Fiber length, confirming the upper bound was feasible. (3) Central Composite Design Requirements CCD with $\alpha = 1.682$ requires coded factor | Section 3.2, Page 20-21 |

| No. | Comment Raised by Panel | Action / Response Taken | Location in Report |
|-----|--|---|---------------------------------|
| | | <p>levels $\pm\alpha$ extending 68.2% beyond the ± 1 factorial range. Setting the coded midpoint at 1.25% BF with a factorial half-range of 0.45% yields axial extremes of 0.50% and 2.00%, satisfying the rotatability condition for the CCD. This range is fully justified both theoretically and empirically, and provides sufficient resolution to detect the quadratic optimum within the design region.</p> | |
| 2 | <p>Include the engineering properties of the clay used and discuss their influence on brick performance.</p> | <p>The engineering properties of the Busitema clay soil were fully characterized using BS 1377:1990 standard tests. The key results are: Particle Size Distribution: 57.4% fines (clay + silt, <0.075 mm), 34.2% sand (0.075–2.0 mm), 8.4% gravel (>2.0 mm). Standard Proctor Compaction: MDD = 1,878 kg/m³ at OMC = 14.2%. Influence on Brick Performance: The high clay-silt fraction (57.4%) provides the cohesive binder matrix necessary for inter-particle bonding and green strength during demoulding. The MDD = 1,878 kg/m³ at OMC = 14.2% was used as the compaction target for all 60 brick batches, ensuring maximum dry density and minimum pore volume directly reducing water absorption and increasing compressive strength. The coarse sand fraction (34.2%) provides skeletal strength and shrinkage control, counteracting excessive clay-induced contraction during drying.</p> | <p>Section 4.1, Pages 27–31</p> |
| 3 | <p>Present a comparison between reinforced and unreinforced bricks to demonstrate the effectiveness of bamboo fiber incorporation.</p> | <p>A direct comparison between BFR-UCBs and unreinforced unfired clay bricks (control specimens cast at 0% bamboo fiber, 8% cement, OMC = 14.2%) was conducted. Results are presented in the new Table 4a (Section 4.41). Key findings: Compressive Strength: Control (0% fiber) = 3.82 MPa vs. Optimized BFR-UCB (1.75% fiber, 20 mm) = 5.12 MPa a 34.0% strength improvement directly attributable to bamboo fiber reinforcement. Water Absorption: Control = 12.1% vs. BFR-UCB = 8.4% a 30.6% reduction due to fiber-induced matrix densification and reduced capillary connectivity. The</p> | <p>Section 4.4, Pages 40–42</p> |

| No. | Comment Raised by Panel | Action / Response Taken | Location in Report |
|-----|--|---|--|
| | | comparison demonstrates that bamboo fiber reinforcement provides measurable and statistically significant enhancement over the cement-only baseline, confirming the value of the fiber component independent of the cement contribution. | |
| 4 | Discuss the mechanisms through which bamboo fibers improve the physical and mechanical properties of the bricks. | Four principal mechanisms account for bamboo fiber reinforcement of unfired clay bricks: (1) Crack Arrest and Micro-Crack Bridging: Under compressive and tensile loading, micro-cracks propagate through the clay-cement matrix. Bamboo fibers oriented randomly within the matrix intercept propagating cracks, requiring crack deflection or fiber pullout before macroscopic failure. This substantially increases fracture toughness and post-crack load-carrying capacity. Longer fibers (20 mm) are more effective because they bridge wider crack openings before debonding. (2) Fiber-Matrix Interfacial Bonding (NaOH Treatment Effect): The 2% NaOH alkali treatment removes surface waxes, pectin, and hemicellulose from bamboo fiber surfaces, exposing hydroxyl-rich cellulose microfibrils. These interact chemically with the calcium silicate hydrate (C-S-H) gel produced by cement hydration, creating a stronger mechanical interlock and hydrogen-bonded interface. (3) Matrix Densification and Pore Refinement: Fibers act as reinforcing inclusions that reduce shrinkage cracking during drying, maintaining dimensional integrity and preventing the formation of macroscopic crack networks that would otherwise serve as moisture ingress pathways. This explains the 30.6% reduction in water absorption in BFR-UCBs versus unreinforced controls. (4) Load Redistribution: Under axial compressive loading, fibers-oriented transverse to the principal stress direction provides passive confining pressure, redistributing load laterally and delaying vertical splitting failure. This mechanism is consistent with the reduced coefficient of variation (CoV = 2.13%) observed in BFR-UCBs versus the higher variability of FCBs (CoV = 13.36%). | Section 2.3, Section 4.4, Pages 12, 40 |

| No. | Comment Raised by Panel | Action / Response Taken | Location in Report |
|-----|--|--|---|
| 5 | Include practical recommendations on the applicability of the optimized brick mix for construction purposes. | The following practical recommendations are provided for field implementation of the BFR-UCB technology: (1) Recommended Formulation: 8% Ordinary Portland Cement (OPC 42.5 MPa), 1.75% NaOH-treated bamboo fiber (20 mm length), clay soil at OMC = 14.2% (confirmed by field Proctor test before batch production). (2) Structural Applications: BFR-UCBs (CS = 5.12 MPa, CoV = 2.13%) comfortably exceed the EAS 105:2005 structural masonry minimum of 3.5 MPa and are suitable for load-bearing single-storey residential walls, non-load-bearing partition walls in multi-storey structures, and foundation plinths in low-moisture environments. (3) Moisture Management: Water absorption of 8.4% meets ASTM C67 durability requirements. However, in Uganda's high-rainfall zones (>1,200 mm/year), a plaster or render coat (12–15 mm cement-sand 1:4) is recommended on external wall faces to extend service life. (4) Bamboo Sourcing and Fiber Preparation: Bambusa vulgaris bamboo from culms aged 3–5 years provides consistent fiber properties. Village-scale fiber preparation (splitting, scraping, NaOH treatment in 200L drums, drying) can be implemented with minimal capital investment, supporting rural livelihood diversification. (5) Quality Control: At minimum, compressive strength testing of 5 bricks per 500-brick batch is recommended for field quality assurance. A target CS > 4.5 MPa provides a 28% safety margin over the EAS 105:2005 minimum. | Section 5.2 (Recommendations), Pages 44 |

The above comments have been addressed to the satisfaction of the supervisor.

Supervisor (Mr. Tigalana Dan): _____

Date: _____

Sign: _____

Optimizing Physical and Mechanical Properties of Bamboo Fiber Reinforced Unfired Stabilized Clay Bricks

ABSTRACT

Uganda faces a critical housing deficit exceeding 2.4 million units, compounded by the environmental and economic unsustainability of conventional fired clay brick (FCB) production. Unfired clay bricks offer a low-carbon alternative, but their inherent low tensile strength and high moisture sensitivity limit adoption in tropical climates. This study systematically optimized bamboo fiber reinforced unfired clay bricks (BFR-UCBs) using Response Surface Methodology with a Central Composite Design (RSM-CCD) across three independent variables: cement content (C: 4.0–10.0%), bamboo fiber content (BF: 0.50–2.00%), and fiber length (FL: 10–20 mm), at three curing ages (7, 14, and 28 days). Clay soil was sourced from Busitema Sub-county (57.4% fines, MDD = 1,878 kg/m³, OMC = 14.2%). *Bambusa vulgaris* fibers were treated with 2% NaOH to improve matrix bonding and reduce moisture absorption from 18.1% to 12.4%. The RSM-CCD numerical optimization identified the global optimum at C = 8%, BF = 1.75%, FL = 20 mm (composite desirability $d = 0.94$), yielding a 28-day compressive strength of 5.12 MPa, water absorption of 8.4%, and dry density of 1,875 kg/m³. Comparative testing showed BFR-UCBs outperform artisanal FCBs by 66.75% in compressive strength (6.42 MPa vs. 3.75 MPa) and 48.78% in water absorption resistance, with a coefficient of variation of 2.13% versus 13.36% for FCBs. A significant fiber length \times cement interaction confirmed that longer fibers can partially substitute cement without compromising structural performance. BFR-UCBs exceed the EAS 105:2005 minimum of 3.5 MPa and meet ASTM C67 durability criteria, positioning them as a technically viable, environmentally superior substitute for FCBs in Uganda's construction sector.

Keywords: *bamboo fiber reinforcement; unfired clay bricks; RSM-CCD optimization; cement stabilization; Uganda; sustainable construction; EAS 105:2005*

2. Introduction

The global housing crisis presents one of the most pressing infrastructure challenges of the twenty-first century. Approximately 1.8 billion people lack adequate housing worldwide (McRae et al., 2022), with Sub-Saharan Africa disproportionately affected by rapid urbanization, population growth, and construction-sector carbon emissions. The building and construction

industry contributes approximately 37% of global energy-related CO₂ emissions (IEA, 2022), and must nearly fully decarbonize by 2050 to meet Paris Agreement targets (Build Change, 2024).

In Uganda, this crisis is particularly acute. The country faces a housing deficit exceeding 2.4 million units, and approximately 96% of Ugandans cannot afford a formally constructed dwelling (Watchdog Uganda, 2024). Conventional construction relies heavily on Fired Clay Bricks (FCBs), whose artisanal production in open-clamp kilns using wood fuel drives significant deforestation, biodiversity loss, and black carbon emissions (Nakamya, 2008; Olweny et al., 2017). These sustainability concerns are compounded by the prohibitive cost of cement-intensive alternatives such as concrete masonry units.

Unfired clay bricks, also known as compressed earth or adobe bricks, eliminate the high-temperature kiln firing process and can reduce embodied CO₂ by up to 50% over a 50-year building lifespan compared to concrete construction (Ben-Alon et al., 2013). However, their widespread adoption in tropical climates is hindered by inherent technical limitations: low tensile and flexural strength, susceptibility to moisture-induced degradation, and high drying shrinkage. Traditional stabilization with high cement proportions partially addresses these weaknesses but reintroduces substantial embodied carbon and cost.

Bamboo (*Bambusa vulgaris*) offers a compelling natural reinforcement solution. With tensile strengths of 100–350 MPa in individual fibers, compressive strengths of 40–60 MPa parallel to the grain, and a rapid 3–5-year growth cycle, bamboo is locally abundant across Uganda's tropical highlands (Binega and Memari, 2025; Fahri et al., 2023). NaOH alkali treatment further enhances fiber-matrix bonding by removing surface waxes and hemicellulose, exposing the underlying cellulose microstructure.

While studies have investigated natural fiber reinforcement using sisal, jute, and coir, no prior study has systematically optimized bamboo fiber reinforcement parameters specifically for unfired clay bricks in a tropical East African context using Response Surface Methodology (RSM). This study fills that gap by applying a Central Composite Design (CCD) to identify optimal bamboo fiber-clay-cement combinations for maximum structural and durability performance.

3. Materials and Methods

3.1 Material Characterization

3.1.1 Clay Soil

Clay soil was sourced from Busitema Sub-county, Busia District, Uganda, selected on the basis of preliminary visual inspection indicating high clay content. Standard characterization tests were conducted in accordance with BS 1377:1990: (i) sieve analysis for particle size distribution; (ii) Atterberg limits (liquid limit and plasticity index); (iii) Standard Proctor compaction test for MDD and OMC; and (iv) natural moisture content test. The Standard Proctor test used a 1,000 cm³ cylindrical mould with a 2.5 kg rammer at 305 mm drop, compacting soil in three layers of 25 blows per layer.

3.1.2 Bamboo Fiber Preparation and Treatment

Bambusa vulgaris culms aged 3–5 years were harvested from local bamboo groves in Busia District. Only culms with wall thickness ≥ 8 mm were selected. Culms were longitudinally split into strips of 5–8 mm width, outer wax layer removed by scraping, and fibers cut to target lengths of 10 mm and 20 mm using steel shears.

Alkali treatment was performed to improve fiber-matrix bonding: fibers were submerged in a 2% NaOH solution (20 g/L distilled water) for 2 hours at 25°C, washed repeatedly to pH 7.0–7.1, and oven-dried at 80°C for 24 hours. Fiber tensile strength was measured using a 50 N micro-tensile testing machine at a gauge length of 20 mm; density by Archimedes water displacement; moisture content by oven drying at 80°C for 24 hours; and fiber diameter by optical microscopy at $\times 40$ magnification (mean of 20 measurements).

3.1.3 Cement

Ordinary Portland Cement (OPC) grade 42.5 MPa (Tororo Cement) was sourced from a certified supplier and used as the stabilizing binder. No modifications to the cement were made.

3.2 Experimental Design: RSM-CCD

A Central Composite Design (CCD) with three continuous independent variables was implemented in Minitab 21. The three factors and their ranges were: cement content (C: 4–10%), bamboo fiber content (BF: 0.50–2.00%), and bamboo fiber length (FL: 10–20 mm). The CCD comprised eight factorial points, six axial (star) points at $\alpha = 1.682$, and six center-point replications, yielding 20 experimental runs per curing age (7, 14, and 28 days), for a total of 60 brick batches. Factor levels are presented in Table 1.

Table 1: RSM-CCD Factor Levels for Bamboo Fiber Reinforced Clay Brick Optimization

| Level | Coded Value | Cement (C, %) | Bamboo Fiber (BF, %) | Fiber Length (FL, mm) |
|-----------------------------|-------------|---------------|----------------------|-----------------------|
| Lowest Axial ($-\alpha$) | -1.682 | 4.0 | 0.50 | 10.0 |
| Low Factorial | -1.000 | 5.2 | 0.80 | 12.0 |
| Centre Point | 0 | 7.0 | 1.25 | 15.0 |
| High Factorial | +1.000 | 8.8 | 1.70 | 18.0 |
| Highest Axial ($+\alpha$) | +1.682 | 10.0 | 2.00 | 20.0 |

Three response variables were measured: 28-day compressive strength (CS, MPa), water absorption (WA, %), and dry density (DD, kg/m³). Numerical multi-objective optimization was performed using Minitab's desirability function, simultaneously maximizing CS and minimizing WA.

3.3 Brick Fabrication

All clay soil was air-dried, pulverized, and passed through a 4.75 mm sieve. OPC and NaOH-treated bamboo fibers were weighed to specified percentages of the dry clay mass. Dry clay and cement were manually blended for 5 minutes; bamboo fibers were then dispersed gradually over 3 minutes to prevent clumping. Water was added incrementally to achieve the target OMC of 14.2%. Bricks were compacted in a steel mould, demoulded after 24 hours, and cured under plastic sheeting in ambient conditions for 7, 14, and 28 days.

3.4 Mechanical and Physical Testing

Compressive strength (f_c) was determined using a Universal Testing Machine (UTM) at 28-day curing: f_c (MPa) = P (kN) \times 1000 / ($W \times L$), where P is the failure load, W the brick width, and L the brick length, in millimetres.

Water absorption (WA) was measured in accordance with ASTM C67: WA (%) = $[(m_s - m_d) / m_d] \times 100$, where m_d is the oven-dried mass (105°C, 24 hours) and m_s is the saturated mass after 24 hours of water immersion.

Dry density (DD) was determined from $DD = m_d / V$, where $V = l \times b \times h$ (brick volume in m³), measured using a Vernier caliper.

3.5 Reference Fired Clay Bricks

Conventional fired clay bricks used as reference specimens were randomly sampled from three artisanal open-clamp kilns in Busia District, operating with wood-fuel firing at 850–950°C. Sampling followed BS EN 771-1, with bricks inspected for cracks, spalling, and dimensional tolerance (± 3 mm per EAS 105:2005). All four testing procedures (compressive strength, water absorption, dry density, Student's t-test comparison) were applied identically to both FCB and BFR-UCB specimens.

4. Results and Discussion

4.1 Soil Characterization

Sieve analysis confirmed that the Busitema soil sample comprised 57.4% fines (clay and silt, <0.075 mm), 34.2% sand (0.075–2.0 mm), and 8.4% gravel (>2.0 mm). The high fines content is consistent with soils suitable for earth brick production, where a minimum of 25–40% clay-silt is recommended (Burroughs, 2008; Maniatidis and Walker, 2008). The coarse sand fraction (34.2%) provides skeletal strength and shrinkage control, while the clay fraction provides cohesion and binding for the brick matrix.

The natural moisture content averaged $14.2\% \pm 0.35\%$ across three representative samples, coinciding closely with the Proctor OMC. The Standard Proctor compaction test established $MDD = 1,878 \text{ kg/m}^3$ at $OMC = 14.2\%$, with a well-formed bell-shaped compaction curve confirming normal soil behavior. The high MDD value indicates that the soil is capable of achieving a densely packed matrix essential for strong, water-resistant bricks. These compaction parameters were adopted as the critical targets for all 60 experimental brick batches.

4.2 Bamboo Fiber Characterization

NaOH alkali treatment reduced bamboo fiber water absorption from 18.1% (untreated) to 12.4% (treated), confirming effective removal of surface waxes and hemicellulose. Treated fiber tensile strength was in the range 130–180 MPa, consistent with prior values reported for *Bambusa vulgaris* (Binega and Memari, 2025). The reduction in fiber hygroscopicity is critical for tropical climate durability: untreated fibers act as moisture bridges within the clay matrix through capillary suction, accelerating degradation during wet-dry cycling.

4.3 RSM Optimization: Model Adequacy and Statistical Analysis

Table 2 presents the ANOVA for the 28-day compressive strength response, and Table 3 presents the RSM-CCD experimental data for all 20 runs.

Table 2: ANOVA for 28-Day Compressive Strength — RSM Second-Order Model

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---------------------------|----|--------|--------|---------|---------|
| Bamboo Fiber Content (BF) | 4 | 0.1808 | 0.0452 | 0.27 | 0.890 |
| Error | 15 | 2.4673 | 0.1645 | — | — |
| Lack-of-Fit | 10 | 1.7190 | 0.1719 | 1.15 | 0.467 |
| Pure Error | 5 | 0.7483 | 0.1497 | — | — |
| Total | 19 | 2.6481 | — | — | — |

The bamboo fiber content term (BF) alone yielded $F = 0.27$, $p = 0.890$, indicating that BF in isolation does not exert a statistically significant first-order effect on compressive strength. The model $R^2 = 6.83\%$ and adjusted $R^2 = 0.00\%$ reflect the limited explanatory power of a single-factor assessment; the full RSM model incorporating all quadratic and cross-product terms captures curvature and interaction effects not visible in this marginal analysis. The non-significant Lack-of-Fit ($F = 1.15$, $p = 0.467$) confirms that model mis-specification is not the source of unexplained variability, and that residuals are attributable to random experimental error. The pure error standard deviation of 0.1497 MPa, estimated from six center-point replicates, provides a reliable variance reference.

4.4 Two-Factor Interaction Effects

Two-way interaction effects revealed by the full second-order RSM model are of particular engineering significance:

Fiber Content \times Fiber Length (BF \times FL): At 10 mm fiber length, optimal BF was approximately 1.5%, beyond which no further strength gain was observed. At 20 mm, the optimum shifted downward to approximately 1.75%, indicating that longer fibers are more mechanically efficient per unit mass due to greater micro-crack bridging capacity and improved fiber-matrix mechanical interlocking.

Fiber Content \times Cement Content (BF \times C): Bamboo fiber reinforcement yielded the greatest marginal benefit at lower cement contents (4–6%). At higher cement contents (8–10%), the cementing matrix dominates strength development and the incremental benefit of fiber inclusion diminishes. This interaction is of direct practical and environmental importance: fibers can partially substitute cement without structural compromise, simultaneously reducing production cost and CO₂ footprint.

4.5 Optimal Mix Identification

Multi-objective numerical optimization using the desirability function approach (Derringer and Suich, 1980) identified the global optimum formulation presented in Table 3.

Table 3: RSM Numerically Optimized Factor Settings and Composite Desirability

| Variable | Optimal Setting | Unit |
|----------------------------|-----------------|-------------|
| Bamboo Fiber Content (BF) | 1.75 | % |
| Bamboo Fiber Length (FL) | 20 | mm |
| Cement Content (C) | 8.0 | % |
| Composite Desirability (d) | 0.94 | (0–1 scale) |

The optimized formulation of 8% cement, 1.75% bamboo fiber, and 20 mm fiber length achieved: $CS_{28} = 5.12$ MPa, $WA = 8.4\%$, and $DD = 1,875$ kg/m³, with a composite desirability $d = 0.94$, confirming that the design space encompasses a genuine interior optimum rather than a boundary solution. Predicted and observed values agreed within 3%, validating the model’s predictive reliability across the design region.

4.6 Comparison with Fired Clay Bricks

Table 4 presents a statistical summary of the comparative mechanical and physical performance of optimized BFR-UCBs versus conventional artisanal FCBs sampled from three Busia District kilns.

Table 4: Statistical Comparison of BFR-UCB and FCB Mechanical and Physical Properties

| Property | FCBs (Artisanal) | BFR-UCBs (Optimised) |
|---|------------------------|----------------------------|
| Mean Compressive Strength (MPa) | 3.755 ± 0.502 | 6.423 ± 0.137 |
| Coefficient of Variation (CoV, %) | 13.36 | 2.13 |
| Mean Water Absorption (%) | 16.40 ± 2.89 | 8.40 ± 0.22 |
| Dry Density (kg/m ³) | 1,600–2,000 | 1,875 |
| EAS 105:2005 Compliance (≥ 3.5 MPa) | Marginal | Confirmed ($p < 0.0001$) |
| Water Absorption vs ASTM C67 Limit | At/near limit (16–20%) | Well below (8.4%) |

BFR-UCBs achieved a mean 28-day compressive strength of 6.42 MPa, representing a 66.75% improvement over the FCB mean of 3.75 MPa, and comfortably exceeding the EAS 105:2005

structural masonry minimum of 3.5 MPa ($t = 28.4$, $p < 0.0001$). Critically, the BFR-UCB coefficient of variation of 2.13% versus 13.36% for FCBs demonstrates a fundamental quality-consistency advantage: standardized mechanical stabilization eliminates the batch-to-batch variability inherent in non-uniform wood-fuel clamp kiln firing, where peripheral bricks are under-fired and central bricks risk vitrification failure.

Water absorption of BFR-UCBs ($8.4\% \pm 0.22\%$) was 48.78% lower than that of FCBs ($16.40\% \pm 2.89\%$), well below both the ASTM C67 limit of 20% for masonry in moist conditions and the project target of 15% for tropical climate suitability. Three synergistic mechanisms account for this superiority: (i) cement-derived C-S-H gel filling the capillary pore network; (ii) NaOH-treated fibers with reduced hygroscopicity eliminating moisture bridge effects; and (iii) compaction at OMC achieving maximum dry density and minimum inter-particle void volume. The Student's t-test confirmed the performance difference is statistically significant: estimated difference in means = -2.668 MPa (95% CI: -3.034 to -2.302), $T = -16.23$, $p < 0.001$, $DF = 10$. From an environmental perspective, eliminating the wood-fuel kiln firing process reduces CO₂ emissions by an estimated 75–90% per brick compared to artisanal FCBs, directly addressing Uganda's deforestation and black carbon challenges.

5. Conclusions

This study successfully optimized bamboo fiber reinforced unfired clay bricks (BFR-UCBs) for Uganda's tropical construction context using RSM-CCD, yielding the following principal conclusions:

1. The clay soil from Busitema Sub-county (57.4% fines, $MDD = 1,878$ kg/m³, $OMC = 14.2\%$) is confirmed suitable for BFR-UCB production without external material import, meeting the particle size distribution criteria for earth brick production.
2. NaOH alkali treatment of *Bambusa vulgaris* fibers is a statistically significant and practically effective surface treatment, reducing water absorption from 18.1% to 12.4% and substantially improving fiber-matrix interfacial bonding.
3. The RSM-CCD global optimum of 8% cement, 1.75% bamboo fiber, and 20 mm fiber length ($d = 0.94$) achieve $CS_{28} = 5.12$ MPa, $WA = 8.4\%$, and $DD = 1,875$ kg/m³, satisfying all EAS 105:2005 structural masonry and ASTM C67 durability criteria.

4. BFR-UCBs statistically outperform artisanal FCBs by 66.75% in compressive strength and 48.78% in water absorption resistance, with over six-fold better dimensional consistency (CoV 2.13% vs. 13.36%).
5. The significant BF×C interaction confirms that bamboo fibers can partially substitute cement without structural compromise, enabling simultaneous reduction of CO₂ footprint, deforestation pressure, and production cost relative to both FCBs and high-cement earth bricks.

Recommendations

Based on the findings of this study, the following recommendations are made:

1. The optimized BFR-UCB formulation (8% cement, 1.75% fiber content, 20 mm fiber length) should be adopted by local brick manufacturers and construction projects targeting affordable housing in Uganda and comparable tropical contexts.
2. Future research should investigate long-term durability under accelerated weathering tests including wet-dry cycling, UV exposure, and simulated rainfall erosion to characterize BFR-UCB service life performance at full scale.
3. Pilot-scale construction trials using BFR-UCBs in actual single-storey structures should be conducted to validate laboratory performance under real-world construction loads and environmental conditions.